The use of carbon fibre reinforced cement as tensile reinforcement for concrete structural elements

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THE USE OF CARBON FIBRE REINFORCED CEMENT AS TENSILE REINFORCEMENT FOR CONCRETE STRUCTURAL ELEMENTS.

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THE USE OF CARBON FIBRE REINFORCED CEMENT AS TENSILE REINFORCEMENT FOR CONCRETE STRUCTURAL ELEMENTS

CONTENTS

Introduction

When carbon fibres were first developed they were hailed as the engineering material of the future, their high strength and modulus combined with low weight seemed to offer unlimited advantages over conventional materials such as steel.

Upto the present day the use of carbon fibres has been in the main limited to the more specialist applications such as the aircraft industry.

This research seeks to explore the possibility of utilising the 'high tech' properties of carbon fibre in the 'low tech' industry of building, and in particular in the forming of reinforced concrete structural elements.

It would be the intention to use carbon fibre in such quantities that the present high costs of the material could be reduced by the economies of scale to create an economically viable alternative to conventional construction materials.

Synopsis

The research programme described in this thesis has two principal objectives :

1) To develop a carbon fibre reinforced composite.

2) To use that composite as the reinforcement for concrete structural elements.

The problem of fully penetrating a tow of carbon fibres with a particulate matrix such as cement is considered and through the study of several alternative methods a method of pre-spreading carbon fibres to allow matrix penetration by the use of low power fan units is developed.

Because of the potential for fibre damage, the fibre spreading approach, although relatively successful, is abandoned in favour of a preimpregnation approach. This uses a Polyvinyl Acetate resin matrix.

As a commercial source of PVA/Carbon fibre Prepreg could not be found, methods of primpregnating carbon fibres are studied and a method of preimpregnating individual tows of continuous fibres in the laboratory is developed.

The properties of the preimpregnated carbon fibres are determined through tensile tests.

The PVA prepreg is utilised to develop a carbon fibre reinforced cement composite material. The effect upon composite properties of varying the fibre volume fraction and of adding PVA resin to the cement matrix are studied.

The structural properties of the composite are determined by an extensive series of tensile and flexural tests.

The use of the composite material in the form of flat sheets to provide the reinforcement for concrete beam elements is studied and the behaviour of the elements is assessed through flexural tests on reinforced beams of different size.

It is determined that delamination of the composite from the concrete is an important factor and a possible explanation for the mode of failure is derived. Beam behaviour is compared with theory to determine the tensile efficiency of the reinforcement.

It is concluded that carbon fibre reinforced cement is a viable structural material, but that much further work needs to be done to fully realise its potential.

CHAPTER ONE

Fibre Reinforced Cement Composites

1.1 Introduction to Composites.

So many materials can be described as composites that it is almost impossible to produce an all embracing definition of a composite material.

It is perhaps easier to understand if the whole range of composites is divided into three main categories :

1) Natural composites.

2) Micro-composites.

3) Macro-composites.

The first group, **Natural composites**, includes materials such as wood or bone in which nature has combined two or more components to produce a material of improved properties.

Micro-composites also include metallic alloys and engineering plastics, but those which are of most interest are the fibre reinforced composites.

Macro-composites are engineering products where two or more materials are combined to give performance in service which is superior to the properties of the individual components. Reinforced concrete would therefore be defined as a macro-composite.

The definition of a composite material adopted here includes the following three criteria :

1) It consists of two or more physically distinct and mechanically separable materials.

2) It can be made by mixing the separate materials in such a way that the dispersion of one material within the other can be done in a controlled way to achieve optimum properties.

3) The composite properties are superior, and possibly unique in some specific respects, to the properties of the individual components.

This research programme is concerned with two of the three categories of composite materials : Micro-composites, in the production of a carbon fibre reinforced cement sheet and Macro-composites in the use of that sheet to reinforce concrete elements.

Fibre reinforced composites can contain either aligned or random fibres. Aligned fibre composites are highly anisotropic as the properties of the composite normal to the fibre direction are limited to those of the matrix material alone.

The advantage of this anisotropy is that it allows the introduction of strength and stiffness into a component specifically where it is required and the fibres are aligned to resist the applied stresses. This leads to the most economic use of the fibre properties.

Aligned fibre composites therefore give the greatest advantages in mechanical properties but the problems of their highly anisotropic nature have to be considered and it may be necessary to introduce fibres not aligned in the directions of the principle stresses in order to cater for secondary stresses in other directions.

Most of the fibre composites in use in the construction industry contain randomly distributed short fibres, as used for example in GRC cladding panels. These offer equal strength in all directions but do not use the fibres in their structurally most advantageous form.

The choice of fibre and matrix type is almost infinite and in theory a composite with any combination of desired properties could be produced by careful selection of the fibre and matrix types.

1.2 The History of Fibre Reinforced Cement Composites in the Construction Industry.

The use of fibre reinforced composites is as old as the construction industry itself. As might be expected, the earliest examples of their use involved those that occurred naturally, for example wood which is one of the commonest naturally occuring fibre reinforced composites.

Naturally occuring fibre composites were soon joined by man-made examples when it was discovered that the addition of straw to mud bricks and horsehair to plaster greatly improved their resistance to cracking. The story of how the Israelites in Egypt were forced, as a punishment, to make bricks without straw is well known.

These examples of composite materials, although man made, utilise fibres that occur naturally. In more recent times artificial fibres have been developed which have material properties far in excess of those used previously.

The availability of new fibres has led to a great boom in the development of fibre reinforced composites. Enormous numbers of composites are available today which utilise many different combinations of fibre and matrix.

In order to keep this introduction brief, the examples given here are limited to those where cement or concrete is used as the matrix and the composites have applications in the construction industry.

Most applications utilise fibres in a form where short or chopped fibres are randomly distributed in a matrix to produce a composite material which is relatively homogeneous and is isotropic. Some however have adapted the technique to produce composites where the fibres are aligned or are in a two dimensional array in order to more efficiently resist the applied stresses.

The following examples of composites are classified according to the fibre type employed.

a) Steel Fibres.

Results of research into the use of steel fibres in concrete were first reported in the early 1960's and ten years later in 1971 the work entered the practical application phase with studies in the USA. The following decade saw a great expansion in the use of Steel Fibre Reinforced Concrete (SFRC), particularly in the USA, but also in other parts of the world.

Research by several workers [1][2][3] has shown that the inclusion of steel fibres in concrete avoids shrinkage cracks and improves the concrete's mechanical properties. It has also been shown that if steel fibres are added to a Reinforced Concrete (R.C.) section then the fibres inhibit cracks close to the reinforcing bars allowing an enhanced steel stress to be used in design.

The material has generally been used in the form of mass concrete with steel fibres randomly dispersed. [4]

The use of SFRC for airport runways is particularly appropriate due to the high flexural strength which is attainable and which is associated with greatly improved pavement life. Another advantage is a reduced thickness requirement, the saving can be as much as 30 - 50% depending upon the strength required.

The greater tensile strain capacity of SFRC results both in a lower maximum crack width and less total crack width than in plain concrete. This allows the spacing of joints to be substantially increased. Fewer joints mean less maintenance and also reduced water penetration of the sub-base.

In highway and runway construction, much work has been done on the application of SFRC overlays and these have performed satisfactorily. A particular example is a trial at the end of a runway at JFK Airport in New York, this was laid in May 1980 and its performance has been described as 'excellent'.

In order to make more economic use of SFRC a modern development is the concept of 'composite paving' [5] which is formed by casting a thin topping layer comprising the relatively expensive high quality SFRC monolithically with an underlying layer of lower quality, less expensive plain concrete.

SFRC has also been employed in the mining industry where it has been used for a number of applications including roof and sidewall stabilisation. The SFRC is applied by the 'Shotcrete' process.

Over irregular surfaces such as tunnel walls the shotcrete process allows the application of a constant thickness of the SFRC. This method is much more economic with materials than the conventional method of laying reinforcing mesh over the high spots and then backfilling with plain concrete.

The shotcreting process tends to result in a preferred two-dimensional fibre alignment perpendicular to the direction of spraying. This accentuates improvements in the strength in the plane of the layer.

Another area where SFRC has found a variety of applications is in the production of precast units. In this field SFRC has a number of advantages for both the manufacturer and the customer.

The manufacturer benefits from fewer breakages in handling, the ability to prduce thinner and lighter sections and the consequential savings in material and transport costs. The customer benefits from increased durability and reduced maintenance.

b) Glass Fibres.

The use of glass fibres to reinforce cement and concrete was first studied in Russia in the late fifties and early sixties. But this early work was plagued by the problem of the glass being attacked by the alkali's present in the hydration products of cement[6]. This meant that although great improvements in mechanical properties were achieved initially, these were rapidly lost as the glass was broken down.

It was not until the development of alkali resisting glass fibres by Pilkington's in collaboration with the Building Research Establishment[7] in the late 1960's and early 70's that Glass Fibre reinforced Cement (GRC) became commercially viable.

These fibres contain an appreciable amount of Zirconium Oxide which endows the fibres with superior resistance to an alkali environment

The development of 'alkali resisting' glass under the trade name 'Cem-fil' has allowed a rapid expansion in the production of GRC. This product has now been further developed, and 'Cem-fil - 2'[e] has improved alkali resistance through a chemical modification of the fibre surface.

It is now widely used in the construction industry, particularly in the production of precast cladding panels. The use of GRC in this application has significant advantages over traditional precast concrete units. GRC panels are considerably lighter and this creates savings in transport, on-site handling, erection and fixings and this weight saving can be carried right through the building to a reduction in foundation requirements. In addition, GRC also offers non-combustability, fire resistance, low maintenance and freedom in design and surface finish.

Cladding panels of this sort are typically manufactured by a spray process where chopped fibres and cement slurry are sprayed onto a mould to form a sheet with a two-dimensional array of reinforcement.

Another technique which is used in the manufacture of larger precast units is that of 'premix' where fibres and matrix are mixed together and are then poured into the mould on a vibrating table. This method is used for example in the manufacture of artificial stone mouldings and sun screens.

A pseudo - structural application of GRC is in the construction of surface bonded masonry walls. This allows the rapid laying of concrete blocks without mortar, the completed panel is then rendered both sides with a GRC/fine aggregate mix. The thickness of the bonding render can be as low as 3mm. This method is widely used in the USA and is marketed in this country through Blue Circle in collaboration with Pilkingtons [9].

Research [10] has shown that the addition of glass fibres to concrete controls the initiation and propagation of cracks and produces significant improvements in both flexural and tensile strength.

The relatively low elastic modulus of glass fibres however precludes their use in truly structural applications where deflection is as important as tensile strength.

Work is continuing on the study of the long term durability of GRC [11] and accelerated aging tests in a number of different environments are being used to gather data on the behaviour of the material.

c) Asbestos Fibres.

Asbestos cement is perhaps the oldest of the modern fibre reinforced cements. It has been known since 1879, but it was not until the early 1900's that technical developments allowed the expansion into large scale production.

Over the years it has had many applications, the best known perhaps being corrugated roofing sheets and pipes.

In recent years it has been realised that there are serious health implications with use of asbestos fibres and in particular with the so called 'blue-asbestos'.

The problem is that the fine fibres remain suspended in the atmosphere and can be inhaled. This can lead to a decrease in the efficiency of the lungs and possible infections. Perhaps more worrying are the reported cases of cancer among people who merely lived close to an asbestos factory. These deaths were traced back in particular to blue-asbestos.

Unfortunately this particular type of asbestos fibre is one that has many advantages as reinforcement as it is the strongest and hardest asbestos, it is also less brittle than others.

These problems have led to much higher safety standards being required in the manufacturing process and this has produced higher costs which have resulted in much reduced production. Most of the firms which formerly manufactured asbestos cement products are now offering asbestos free alternatives.

d) Other Fibres.

As mentioned earlier, one of the first composite materials to be used by man was wood. It is perhaps not suprising that some modern research has been directed to investigating whether wood fibres can be used to reinforce cement and concrete.

The workers found that although wood fibres have relatively poor mechanical properties they do have several advantages,[12][13], namely low cost, low density and low energy demand during manufacture which make them attractive. The use of wood fibres is also more environmentally attractive as they are a renewable resource, whereas most other fibre sources are not.

The fibres are obtained by a wood pulping process, similar to that used in the paper industry. and the fibre strength is comparable with some forms of asbestos.

It was found that such fibres could be used to create a composite material with reasonable mechanical properties.

Fibres which have low E-values, for example nylon and polypropylene have been used in combination with cement, not to provide tensile reinforcement but to impart increased resistance to impact.

These fibres have the advantage of being inert to alkalinity and most forms of chemical attack. When used in a cement/concrete matrix they limit crack propagation and retain residual strength after cracking so that members remain virtually in one piece after fracture.

The problems associated with the use of asbestos fibres have opened up a huge potential market for alternative fibre types. One possible contender in this market is polypropylene.

The performance of polypropylene reinforced cement corrugated sheeting has been studied [14] and it was found that this material was capable of sustaining loads greatly in excess of those required under the relevant British Standards and was extremely tough.

The impact resistance of polypropylene/concrete composites makes them ideally suited to forming piling shells. Such units are subjected to repeated hammer blows as they are driven into the ground. The company which manufactures them has found a 40% improvement in impact strength compared to traditional steel mesh reinforced shells.

1.3 Carbon Fibre Reinforced Cement.

A Review of Previous Work.

Carbon fibres have many properties which make them attractive as an engineering material. Their combination of high strength, high modulus, low weight and resistance to chemical attack has prompted several workers to investigate their possible use in the construction industry.

During the 1970's much research was directed towards incorporating carbon fibres into a cement matrix.

Early work by Majumdar and Rayment [15] at the Building Research Establishment produced carbon fibre reinforced cement composites with fibre volume fractions of around 3.0% using a hand lay-up technique. They found that the tensile strength of the composite was increased over that of the unreinforced matrix by a factor of five and that the elastic modulus was doubled. They noted that the durability of Carbon Fibre Reinforced Cement (CFRC) was an important factor and in tests they found no fall off in properties after one year in air or water at 18°C and only a slight fall off after immersion in water at 50°C for one year.

Briggs, Bowen and Kollek [16] working at about the same time studied the properties of CFRC produced using a filament winding technique. They noted that the composite modulus could be predicted by the 'Law of Mixtures'. They also found that the inclusion of fibres increased the stress at which matrix cracking first occurred and that the work of fracture was increased by several orders of magnitude.

They further determined that multiple cracking of the matrix had no deleterious effect on composite properties and that the composite had good fatigue resistance in bending.

Waller,[17][18] in collaboration with others, considered possible applications of CFRC and in particular studied the potential of carbon fibre reinforced precast floor units. He concluded that although such a use was theoretically possible it was precluded at that time by the high cost of carbon fibres.

The structural properties of CFRC were investigated by Sakaar & Bailey [19] who carried out a number of tensile and flexural tests on specimens over a range of fibre volume fractions. They found that the composite moduli compared well with theory but that the tensile strength, although reasonable, was only just over half of its theoretical value.

In further work Dr Briggs [20] considered possible applications of CFRC and he made up and tested samples of pipes and scaffold boards. These were compared with samples made from the traditional materials of asbestos cement and wood respectively and he concluded that although CFRC could compete in terms of stuctural performance, the cost of the carbon fibres meant that they could not be commercially viable.

In a comprehensive review of carbon fibre reinforced cement in 1977 Dr Briggs [21] described several fabrication techniques which had been successfully applied. These ranged from simple hand lay-up through to filament winding which he described as the 'most elegant' solution.

He considered the performance of the composites and discussed theoretical considerations which could affect that performance. He concluded that by choosing fibre types a family of composite materials with a range of properties could be produced. He said that the mechanical properties could be described by the theories of brittle matrix composites and that the short term durability had been established.

Although potential applications in structures existed, Dr Briggs concluded that the price of carbon fibres would need to fall before these became commercially viable.

In previous work in 1981 the author [22] investigated the possibility of using carbon fibre reinforced cement sheets as reinforcement for concrete beams. Although this had only limited success it was thought that it showed enough potential to justify further research.

It can be seen that although considerable theoretical work has been carried out on the study of CFRC and practical uses have been suggested, the high cost of the carbon fibres has prevented any of these suggestions being commerically viable.

Proposed Application

The use of fibre reinforced cement and concrete in the construction industry has generally been confined to non-structural applications. For example, corrugated roof panels and pipes in the case of asbestos and cladding panels in the case of GRC.

Carbon fibres have excellent structural properties and their availability opens up the possibility of the *structural* use of fibre reinforced cement composites in the construction industry. The challenge is to find an application which makes full use of the structural advantages of carbon fibres, and which can overcome the drawback of their initial high cost.

As discussed in the previous section, many possible applications have been suggested for CFRC though none have actually been developed in practice because the relatively high material cost of carbon fibres has made them uneconomic.

One of the principle reasons for the high cost of carbon fibres is that until now their use has been confined to the more specialised areas such as the aircraft industry, consequently demand has been fairly low and they have been produced in relatively small quantities. It is thought that if an end use can be found which would greatly increase demand then the unit costs of manufacture would fall.

This research is directed towards meeting the challenge of utilising the undoubted advantages of carbon fibres and in such a way that they can compete commercially with more traditional materials.

To be successful the end use which is derived must satisfy the following criteria:

1) It must make full use of the structural properties of carbon fibre.

2) It should offer advantages over more traditional alternative materials.

3) It should be able to compete economically with those traditional materials.

Reinforced concrete is one of the most widely used structural materials in the construction industry. Concrete which is naturally weak in tension is reinforced by bars of mild or high yield steel to form efficient structural elements which utilise the compressive strength of the concrete and the tensile strength of the steel.

The construction of reinforced concrete floor slabs in multi storey buildings is one area where it is thought that carbon fibre reinforced cement may be able to offer a realistic alternative to current practice.

The CFRC would take the form of a flat or profiled sheet which would contain continuous carbon fibres, aligned to resist the principle stresses, which would act as both tensile reinforcement and as a system of permanent formwork for the concrete.

The use of CFRC in this situation appears to offer several advantages over traditional methods.

By acting as both formwork and tensile reinforcement, the CFRC would greatly simplify the construction of such floor slabs.

Labour costs would be reduced as the reinforcement for the concrete could be placed by unskilled operatives instead of highly skilled steel fixers.

Savings in construction time would result as the erection of formwork and the placing of reinforcement would be combined in a single operation. Further savings in construction time should be possible as the need to remove the formwork once the concrete has hardened is obviated.

As carbon fibres are inert to the alkaline environment of cement and do not corrode, they do not require the extra concrete cover which is needed to protect steel against corrosion and fire. Floor slabs could therefore be thinner, greatly reducing the dead load to be carried by the supporting beams and columns. This would produce savings in material costs and mean secondary savings elsewhere in the structure.

An additional advantage is, that being placed on the underside of the floor slab, the reinforcement is in the structurally most advantageous position, offering the greatest lever arm.

To summarise, the proposed end-use is a system of shuttering which would provide all the tensile reinforcement for flat slab construction. This would utilise a carbon fibre reinforced cement composite in the form of a flat or profiled sheet containing continuous fibres aligned in the direction of the principle stresses.

It is hoped that the savings in construction time and costs offered by such a system would offset the initially higher cost of the materials.

In order to simplify the research, the investigation is limited initially to one particular format, namely reinforcement for a simply supported slab spanning in one direction only.

If the material is successful in this application then there would seem to be no reason why the system could not be extended to other reinforced concrete elements such as :

Floor slabs spanning in two directions.

Beams, where a 'U' shaped mould could provide both tensile and shear reinforcement.

Columns, where a circular or square tube of CFRC could act as formwork and reinforcement.

CHAPTER TWO

Theoretical Aspects of Fibre Reinforced Composites

2.1 Introduction.

Many properties of fibre reinforced composites are dependant upon geometrical aspects of the composite make-up. For example, fibre diameter, fibre length, fibre volume fraction and the orientation and packing arrangement of the fibres.

Geometrical aspects can be controlled during the manufacture of the composite. For example the designer may choose to use a random distribution of short fibres or alternatively to use continuous aligned fibres, the choice made can greatly affect the structural properties of the finished product.

Composite behaviour is also dependant upon the structural properties of the components and on the nature and strength of the interface between them. The distribution of stress and strain in particular is influenced by the properties of the fibre/matrix interface.

The first part of this chapter deals with the geometrical aspects of composites, in particular, the fibre volume fraction. The mechanisms of fibre reinforcement and their effects upon the composite properties are then discussed.

Failure processes are described and discussed with particular reference to the critical fibre volume fraction and multiple fracture of the matrix.

2.2 Geometrical Aspects.

Advanced composites are generally made up in layers of fibres and matrix called laminae, these are laid in such a way as to achieve optimum performance.

The fibres in these laminae could be randomly orientated or be aligned in a particular direction. Where optimum structural properties are required continuous aligned fibres are used.

When several laminae are stacked together the resulting composite is called a laminate, the properties of which depend upon the properties and alignment of each lamina.

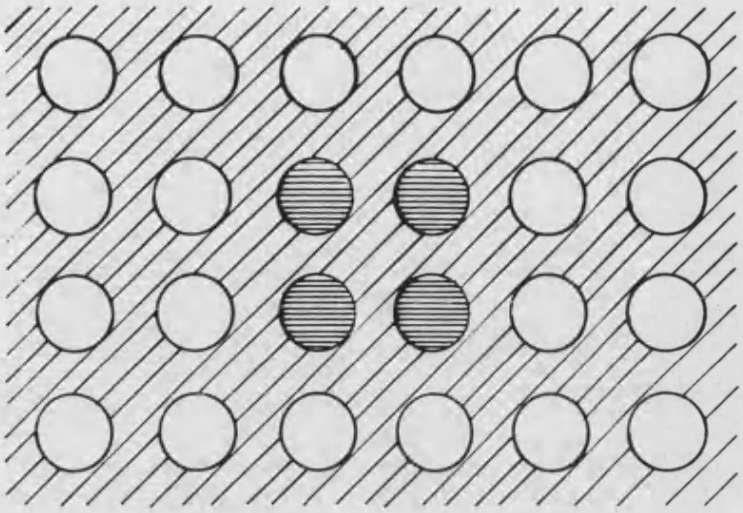
Consider a lamina in which the fibres are continuous and are aligned parallel to each other. In an ideal composite the fibres can be considered to be arranged in a square or hexagonal lattice as shown in Fig 2.1.

If the cross sectional area of such a composite is A_c and the areas of fibre and matrix are A_f and A_m respectively, then the fibre volume fraction V_f is given by :

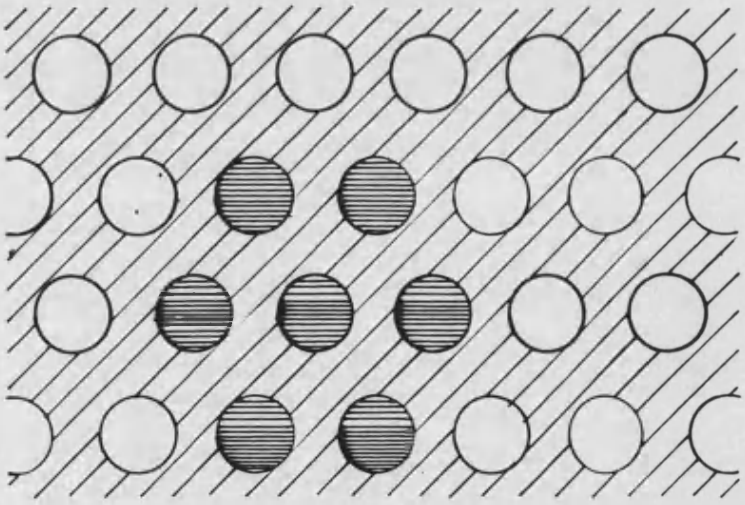
$$V_f = A_f/A_c$$

similarly :

$$V_m = A_m/A_c \qquad \text{and } V_m = (1 - V_f)$$



a) Square Array.



b) Hexagonal Array.

FIG. 2.1 Lattice Arrangements.

In the lattice arrangements illustrated in Fig 2.1 the fibre volume fraction is related to the fibre radius 'r' by the equations :

$$V_f = [2\pi/\sqrt{3}]\ (r/R)^2 \qquad \text{(Hexagonal)} \qquad (2.1)$$

$$V_f = \pi\ (r/R)^2 \qquad \text{(Square)} \qquad (2.2)$$

where R is the centre to centre spacing of the fibres.

The maximum fibre volume fraction occurs when the fibres are touching ie. when R = 2r. In this case, using equations (2.1) and (2.2), : $V_f(max)$ = 0.907 and 0.785 for the hexagonal and square arrays respectively.

These maximum values are useful to note, but experimental studies of the distribution of fibres in unidirectional laminae reveal that if these ideal packing arrangements do occur it is only in very small, localised, areas.

With low fibre volume fractions the packing is likely to be irregular with densly packed fibres in some areas and matrix rich zones in others.

Because of the irregular packing of fibres in practical composites it is difficult to obtain fibre volume fractions in excess of 0.7 (70 %). For commercial composites this figure should be regarded as a practical limit.

Fibre spacing is important when considering the 'wetting' of the fibres by the matrix. This is achieved by the matrix material flowing between the packed fibres. Consequently, if small diameter fibres are used with a high volume fraction the inter fibre spacing is very small and this can cause problems with matrix penetration.

Resin matrices, being free flowing, can tolerate fairly small fibre spacings but if the matrix material is particulate (eg cement), then the spacing between fibres must be increased.

For full penetration with a particulate matrix, the fibre spacing must be at least equal to the particle size. This requirement puts a limit on the maximum fibre volume fraction which is attainable.

For example, if the matrix particle diameter is 'D' then the minimum centre to centre spacing of the fibres is :

$$R = 2r + D$$

Therefore, substituting for R in equations (2.1) and (2.2), the maximum fibre volume fractions are given by :

$$V_{fmax} = [2\pi/\sqrt{3}]\ (r/(2r+D))^2 \qquad \text{(Hexagonal)} \qquad (2.3)$$

$$V_{fmax} = \pi\ (r/(2r+D))^2 \qquad \text{(Square)} \qquad (2.4)$$

Thus it can be seen that the larger the particle diameter, the lower the volume fraction which can be achieved.

If these equations are applied to a theoretical carbon fibre/cement composite which has a fibre radius, r = 4 μm and the diameter of the cement particles, D = 40 μm (say),

Then $V_{f max}$ is thus 0.0252 (2.52%) and 0.0218 (2.18%) for hexagonal and square packing arrangements respectively. These seem extremely low, but in reality a cement will contain a range of particle sizes and consequently higher volume fractions may be possible.

If voids occur in a composite these can have an important effect upon the properties. According to Judd & Wright [23], regardless of fibre and matrix type, the interlaminar shear strength of a composite decreases by about 7% for each 1% voids content, up to a maximum voids content of about 4%.

Voids in composites are usually of two types, they either occur between laminae and in resin rich areas or they run along individual fibres. In this latter case they may be spherical or be elongated into elipsoidal cavities parallel to the fibres.

Examples of voids in carbon fibre reinforced cement, photographed using a Scanning Electron Microscope, are shown in Fig. 2.2

Voids can be formed during composite manufacture by incomplete penetration and wetting of the fibres by the matrix. This leads to entrappment of air and is quite likely to occur with a particulate matrix such as cement.

It is likely therefore that the presence of voids in CFRC will have a significant effect upon the composite performance.

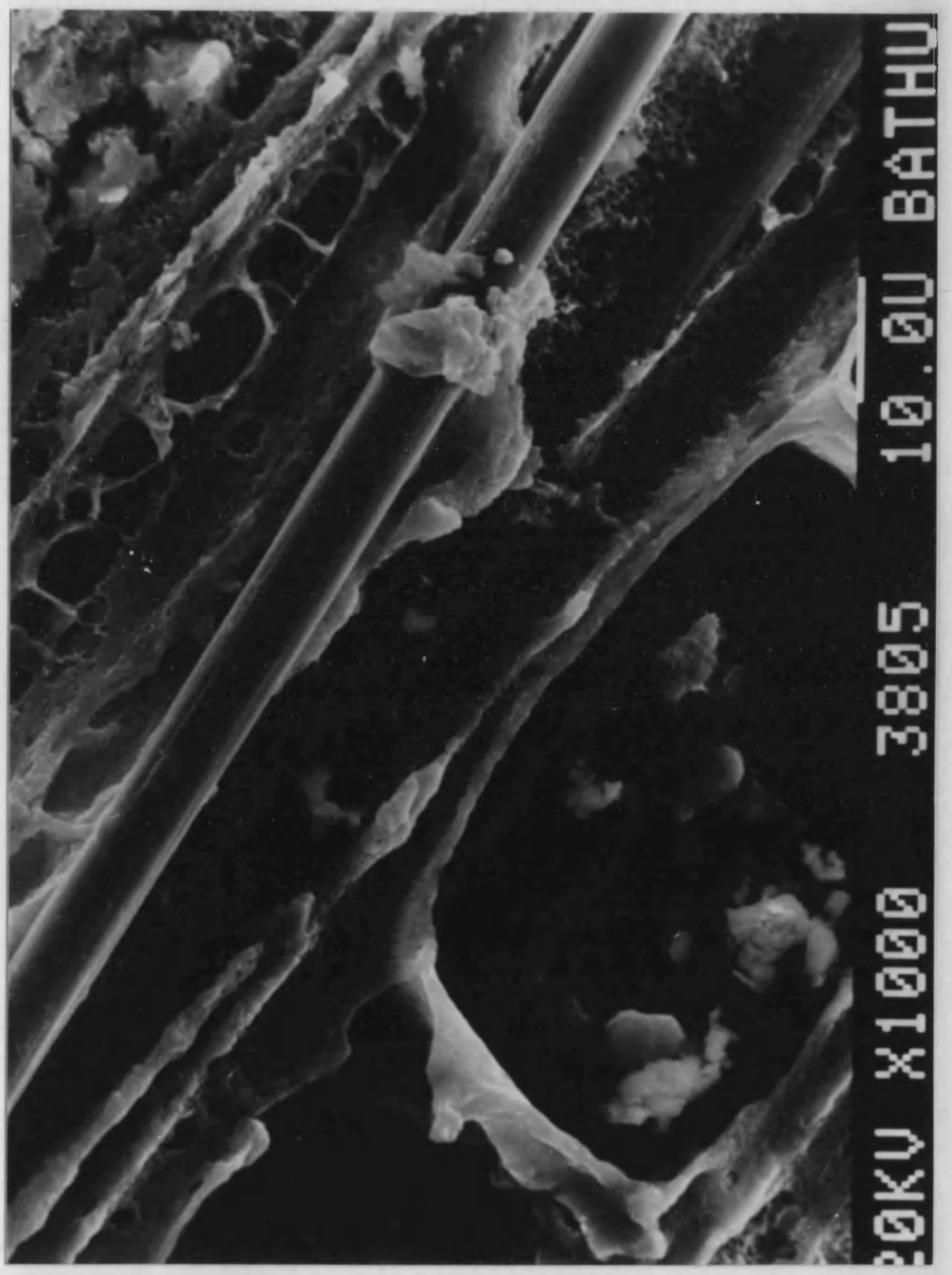


FIG. 2.2 S.E.M. Photograph of Voids Formed in Carbon Fibre Reinforced Cement.

2.3 Elastic Properties of Composites.

The distribution of stress and strain within a composite can be determined in terms of the distribution and volume fraction of the fibres and the elastic properties of the fibres and matrix.

Composite behaviour can also be predicted from an examination of the reinforcement processes and from consideration of the fibre/matrix interface.

In this section the composite properties are derived, initially by reference to the properties and volume fraction of the constituents and then by a more detailed consideration of the composite mechanics.

In order to calculate the stress/strain distribution the following assumptions about the fibre/matrix interface are necessary :

i) Fibre and matrix behave elastically.

ii) The fibre/matrix interface is infinitesimally thin.

iii) Bond between fibre and matrix is perfect and the matrix strain is therefore equal to the fibre strain.

iV) Matrix material close to the fibres has the same properties as it has in the bulk form.

V) The fibres are arranged in a regular or repeating array.

Consider a unidirectional lamina containing continuous fibres as shown in Fig. 2.3 .

When a tensile load is applied parallel to the fibres then according to assumption (iii) the composite strain ϵ_1 will be equal to that in the matrix and in the fibre.

ie. $\epsilon_1 = \epsilon_m = \epsilon_f$

If fibre and matrix behave elastically, then the corresponding stresses in fibre and matrix are given by :

$$\sigma_f = E_f\epsilon_1, \quad \text{and} \quad \sigma_m = E_m\epsilon_1. \tag{2.5}$$

From this it can be seen that if the fibre modulus is greater than that of the matrix then the stress induced in the fibre at equal strain will be greater. This is the fundamental basis of reinforcement where the fibres are used to carry the bulk of the load.

If the load applied to a composite of cross sectional area 'A' is 'P' then the average stress is given by :

$$\sigma_1 = P/A$$

since $P = P_f + P_m$

and $P_f = \sigma_f A_f$, and $P_m = \sigma_m A_m$

$$P = \sigma_f A_f + \sigma_m A_m \tag{2.6}$$

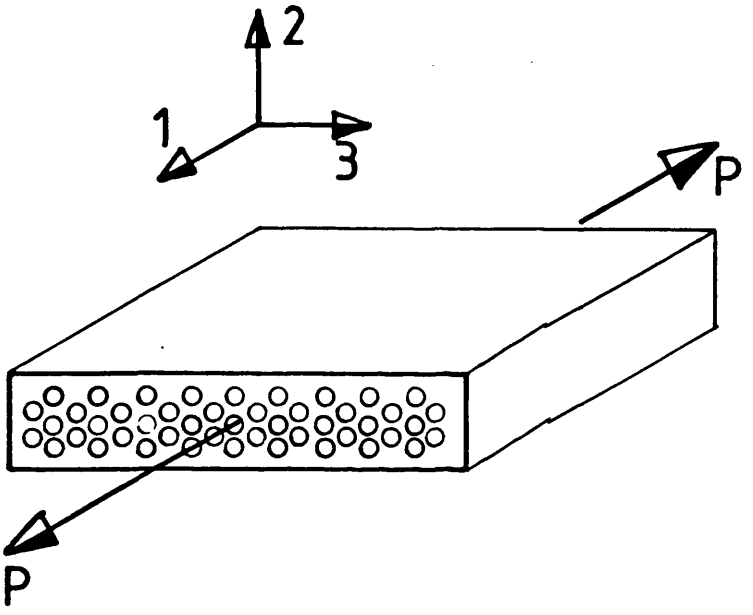


FIG. 2.3 Unidirectional Lamina.

The composite stress $\sigma_1 = E_1\epsilon_1$, and, substituting from equation (2.5) in equation (2.6) gives :

$$E_1 = E_f(A_f/A) + E_m(A_m/A)$$

$$\text{ie. } E_1 = E_fV_f + E_mV_m \qquad (2.7)$$

This equation is known as the ***'Rule of Mixtures'***, and since $V_m = (1 - V_f)$. it can also be written :

$$E_1 = E_fV_f + E_m(1 - V_f) \qquad (2.8)$$

It should be noted that this analysis is based on the assumption that equations (2.5) are valid. In reality this will not be true since differences in the poissons ratios of the two components will result in additional stresses which have not been taken into consideration.

The error due to these differences in poissons ratio is however small, and is likely to be less then 1 or 2%. Equations (2.7) & (2.8) can therefore be taken as being sufficiently accurate.

In order to calculate the composite properties in a direction normal to the fibre direction it is necessary to make the further assumption that the stresses in both components are equal.

This is only true in a model in which fibres and matrix are assumed to be arranged in a 'sandwich' with all the fibres together in a band normal to the direction of the applied stress. This arrangement is illustrated in Fig 2.4.

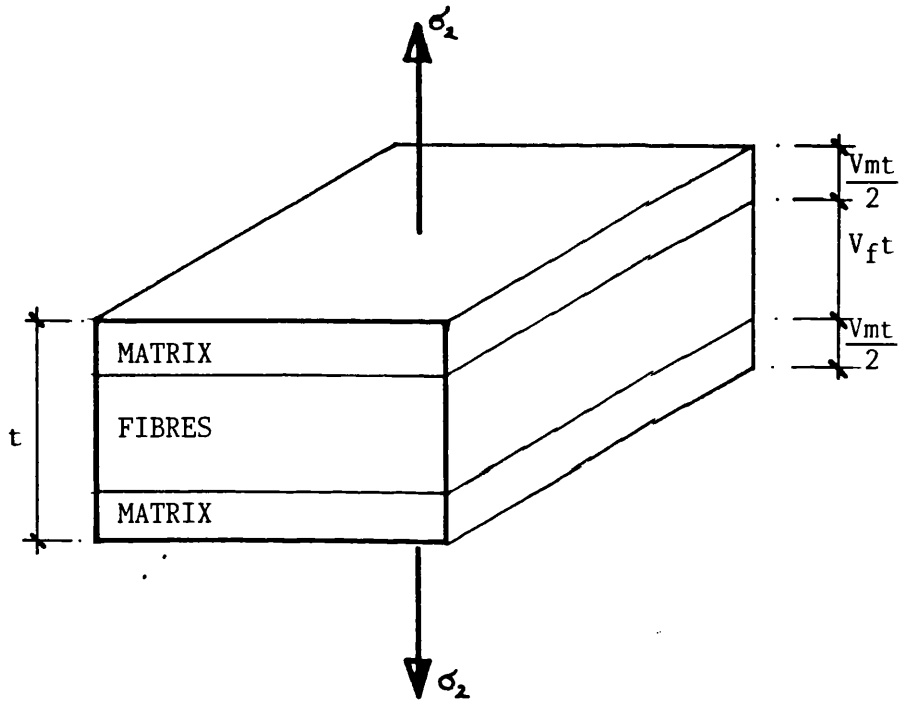


FIG. 2.4 Composite 'Sandwich' Model.

If the fibre and matrix stresses are assumed to be equal, the corresponding strains are given by :

$$\epsilon_f = \sigma_2/E_f, \quad \text{and} \quad \epsilon_m = \sigma_2/E_m. \tag{2.9}$$

The total composite displacement is given by the sum of the displacements in the fibres and the matrix. ie. $\epsilon_f(V_f t)$ & $\epsilon_m(V_m t)$ respectively, so that the composite strain is given by :

$$\epsilon_2 = V_f\epsilon_f + V_m\epsilon_m \tag{2.10}$$

Since $E_2 = \sigma_2/\epsilon_2$, substituting for ϵ_2, ϵ_f & ϵ_m in this equation gives :

$$1/E_2 = V_f/E_f + V_m/E_m \tag{2.11}$$

A similar equation can be derived for E_3.

When the fibre modulus is much greater than the matrix modulus (as would be the case for a carbon fibre/cement composite) the fibre component of equations (2.10) & (2.11) becomes less important and the composite modulus then approximates to the matrix modulus divided by the volume fraction.

ie, if $E_f \gg E_m$, $E_2 \simeq E_m/V_m$

In effect it can be assumed that the transverse moduli are proportional to the matrix modulus.

2.4 Theory of Reinforcement.

The analysis described in the previous section assumed that the fibre/matrix bond was perfect, in reality this may not be the case.

The nature of the fibre/matrix interface depends upon the nature and properties of both the fibre and the matrix. Each combination of different components will have different characteristics.

In some cases the fibres may react with the matrix and form a chemical bond, in others there may be no chemical bond and any grip will depend upon the surface qualities of the fibre.

The first method of explaining the reinforcing effect of fibres was described by Cox in 1952 [24]. This 'shear lag theory' was based entirely upon elastic interactions and really only explained composite behaviour at low stresses.

In the 1960's Cotrell, Kelly and Outwater [25] developed theories which described reinforcement by slip. These were based on matrix plasticity at the fibre surface near the fibre ends and on frictional sliding of the fibre ends.

The theory of reinforcement by slip[26] is described here and this gives the modulus and strength in the fibre direction for aligned, short fibre composites.

This is followed by an elastic analysis of composite behaviour at low stresses.

2.5 Reinforcement by Slip.

Consider a composite containing short, straight fibres in a matrix which is entirely elastic. The fibres are assumed to be perfectly elastic up to their breaking point, (as is the case with carbon fibres).

The behaviour of the composite under load can be studied by means of a model in which the composite is assumed to be made up of many 'composite elements', each containing a single short fibre.

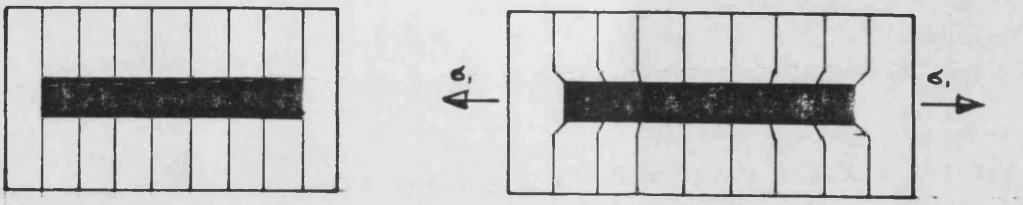
This idealised 'composite element' is illustrated in Fig. 2.5(a).

It is assumed that, when a tensile stress 'σ_1' is applied to the ends of the composite element, slippage occurs between the matrix and fibre in the region close to the ends of the fibre and the matrix distorts as shown in Fig. 2.5(b).

Where slippage occurs the shear stress along the interface between fibre and matrix is assumed to have a constant value 'τ_i'. In the centre region of the fibre, no slip occurs and the interfacial shear stress is zero.

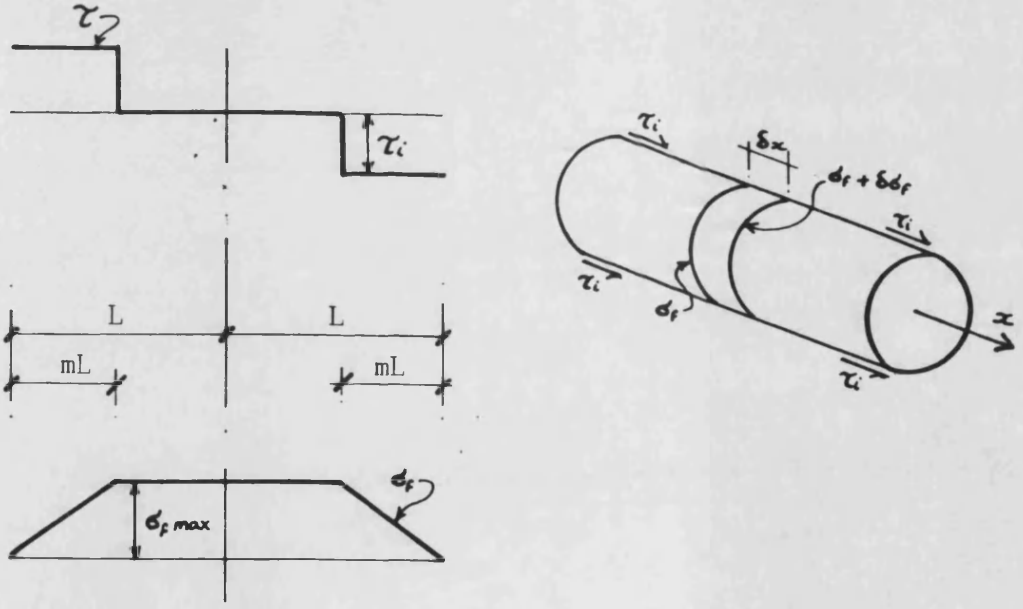
The tensile stress which is induced in the fibre is assumed to be zero at the fibre ends and to gradually increase over the length of fibre where slip is occurring to reach a constant value 'σ_{fmax}' in the centre region.

The distributions of interfacial shear stress and fibre tensile stress are illustrated in Fig. 2.6(a) where half the fibre length is 'L' and the length over which slip occurs is 'mL'.



(a) Unstressed. (b) Stressed.

FIG. 2.5 Composite Element.



(a) Stress Distribution. (b) Fibre Element.

FIG. 2.6

If a short element of the fibre in the zone where slip occurs is considered, as shown in Fig. 2.6(b), the tensile stress in the fibre element increases along its length such that over a length δx the fibre tensile stress increases from σ_f to $(\sigma_f + \delta\sigma_f)$.

If it is assumed that at any point along the length of the element the interfacial shear force is equal to the tensile force in the fibre then :

$$\pi r^2 \, \delta\sigma_f = - 2\pi r \, \delta x \, \tau_i \qquad (2.12)$$

$$\text{ie.} \quad \delta\sigma_f/\delta x = - 2\tau_i/r \qquad (2.13)$$

At the fibre ends $x = L$ and the tensile stress in the fibre, $\sigma_f = 0$. Therefore, if equation (2.13) is integrated, the fibre tensile stress at a point a distance 'x' from the centre is given by the expression :

$$\sigma_f = 2\tau_i(L - x)/r \qquad (2.14)$$

where 'x' is in the range : $(1 - m)L < x < L$.

Over the centre region of the fibre, where no slip occurs, (ie. $x < (1 - m)L$) the tensile stress in the fibre is assumed to be constant and to have the value $\sigma_{f\max}$.

Therefore, equating the tensile and interface shear forces gives :

$$\pi r^2 \sigma_{f max} = 2\pi r \, (mL) \, \tau_i \qquad (2.15)$$

$$\therefore \quad \sigma_{f max} = 2m(L/r) \, \tau_i \qquad (2.16)$$

The expression L/r is generally referred to as the 'fibre aspect ratio' and is designated by the symbol 's' so that the fibre stress in the centre region is given by the expression :

$$\sigma_{f max} = 2ms\tau_i \qquad (2.17)$$

The relationship between interfacial shear stress and fibre tensile stress over the full length of the fibre element is therefore described by the two equations (2.14) and (2.17).

This analysis has only considered 'composite elements' containing individual short fibres. It must now be extended to the general case of a composite material which is made up of many of these elements arranged in a parallel array.

If a section is cut through such a composite at any point along its length, in a direction normal to the fibre direction, it will, in theory, intersect the fibres at all possible points along their length, provided that the number of fibres is sufficiently large.

If the average fibre tensile stress is '$\bar{\sigma}_f$' then the total load which is carried by the fibres 'P_f' will be given by the expression :

$$P_f = AV_f\bar{\sigma}_f \qquad (2.18)$$

where: A = *Composite area.*
V_f = *Fibre volume fraction.*

Similarly, the element of load carried by the matrix component 'P_m' is given by :

$$P_m = AV_m\bar{\sigma}_m \qquad (2.19)$$

where: $\bar{\sigma}_m$ *is the mean matrix stress.*

The total load on the composite 'P_1' is given by the sum of these expressions such that :

$$P_1 = P_f + P_m = A(V_f\bar{\sigma}_f + V_m\bar{\sigma}_m) \qquad (2.20)$$

From Fig. 2.6 it can be seen that the average tensile stress for each fibre is equivalent to the area under the graph divided by the fibre length such that :

$$\bar{\sigma}_f = [2\sigma_{fmax}(1 - m)L + \sigma_{fmax}mL]/2L$$

$$\therefore \quad \bar{\sigma}_f = \sigma_{fmax}(1 - {}^{m}/_{2}) \qquad (2.21)$$

From equation (2.20) it can be seen that the composite tensile stress can be obtained by dividing the applied load by the composite area such that :

$$\sigma_1 = (V_f\bar{\sigma}_f + V_m\bar{\sigma}_m) \qquad (2.22)$$

The value of $\bar{\sigma}_f$ obtained from equation (2.21) can then be substituted in this expression to give :

$$\sigma_1 = V_f\sigma_{fmax}(1 - {}^{m}/_{2}) + V_m\bar{\sigma}_m \qquad (2.23)$$

From equation (2.17) it can be seen that $m = \sigma_{fmax}/(2s\tau_i)$. Therefore, substituting for m in equation (2.23) gives :

$$\sigma_1 = V_f\sigma_{fmax}[1-(\sigma_{fmax}/4s\tau_i)] + V_m\bar{\sigma}_m \qquad (2.24)$$

In the centre region of each fibre no slip occurs so that it can be assumed that the fibre and matrix strains are equal, and are equal to the composite strain 'ϵ_1' such that :

$$\epsilon_1 = \sigma_{fmax}/E_f = \bar{\sigma}_m/E_m$$

Rearranging these expressions gives :

$$\sigma_{fmax} = \epsilon_1 E_f \qquad \bar{\sigma}_m = \epsilon_1 E_m$$

Therefore, substituting for σ_{fmax} and $\bar{\sigma}_m$ in equation (2.24) gives :

$$\sigma_1 = V_f\epsilon_1 E_f[1 - (\epsilon_1 E_f/4s\tau_i)] + V_m\epsilon_1 E_m$$

This equation can be rearranged to give the general expression for fibre stress :

$$\sigma_1 = \epsilon_1[V_f E_f + V_m E_m] - V_f(\epsilon_1^2 E_f^2/4s\tau_i) \qquad (2.25)$$

If the situation is such that slip occurs along the whole length of the fibre, ie. m = 1 , then the distribution of tensile stress in the fibre would be as illustrated in Fig 2.7.

The mean fibre stress in this case is simply : $\bar{\sigma}_f = \sigma_{fmax}/2$, and therefore, substituting in equation (2.22) the composite stress 'σ_1' is given by :

$$\sigma_1 = V_f(\sigma_{fmax}/2) + V_m\bar{\sigma}_m \qquad (2.26)$$

From equation (2.17) σ_{fmax} is defined as : $\sigma_{fmax} = 2ms\tau_i$. Therefore, when m = 1 the expression for composite stress becomes :

$$\sigma_1 = V_f(s\tau_i) + V_m E_m\epsilon_1 \qquad (2.27)$$

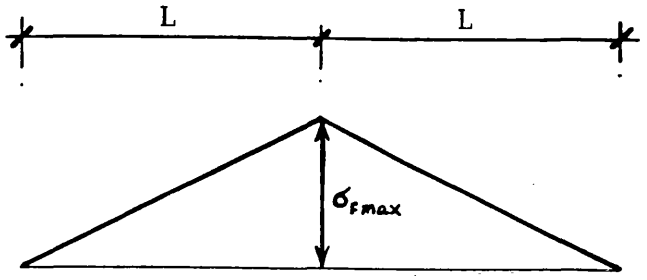


FIG. 2.7 Fibre Tensile Stress When 'm = 1' .

The expression for the composite stress given in equation (2.25) has been derived for a composite where the reinforcement is provided by short fibres.

It can also be applied to composites which contain very long or continuous fibres. In this case, the fibre aspect ratio $s \to \infty$ and equation (2.25) becomes :

$$\sigma_1 = \epsilon_1[V_f E_f + V_m E_m]$$

Therefore, as the composite modulus $E_1 = \sigma_1/\epsilon_1$ this expression becomes :

$$E_1 = [V_f E_f + V_m E_m]$$

ie. A composite which is reinforced by very long or continuous fibres follows the **'Rule of Mixtures'**.

2.6 Composite Poisson's Ratio.

When a material is subjected to a tensile stress in one direction, it will extend in that direction and contract in the direction normal to the force.

Similarly, when a stress σ_1 is applied to a composite of thickness 't' both the fibres and the matrix will contract in the direction normal to the applied stress. The fibres by an amount $U_f = v_f \epsilon_1 V_f t$, and the matrix by an amount $U_m = v_m \epsilon_1 V_m t$, where v_f and v_m are the Poisson's ratios of fibres and matrix respectively.

This is illustrated in Fig. 2.8

The total composite contraction U_2 in the direction normal to the applied force will be the sum of U_m and U_f. This gives a composite strain in that direction of $\epsilon_2 = U_2/t$.

Therefore, $\epsilon_2 = - (V_f v_f + V_m v_m)\epsilon_1$ (2.28)

Where the minus sign denotes contraction.

And, since $v_{12} = - \epsilon_2/\epsilon_1$

The composite Poisson's ratio v_{12} is given by :

$v_{12} = (V_f v_f + V_m v_m)$ (2.29)

Symmetry gives : $v_{12} = v_{13}$.

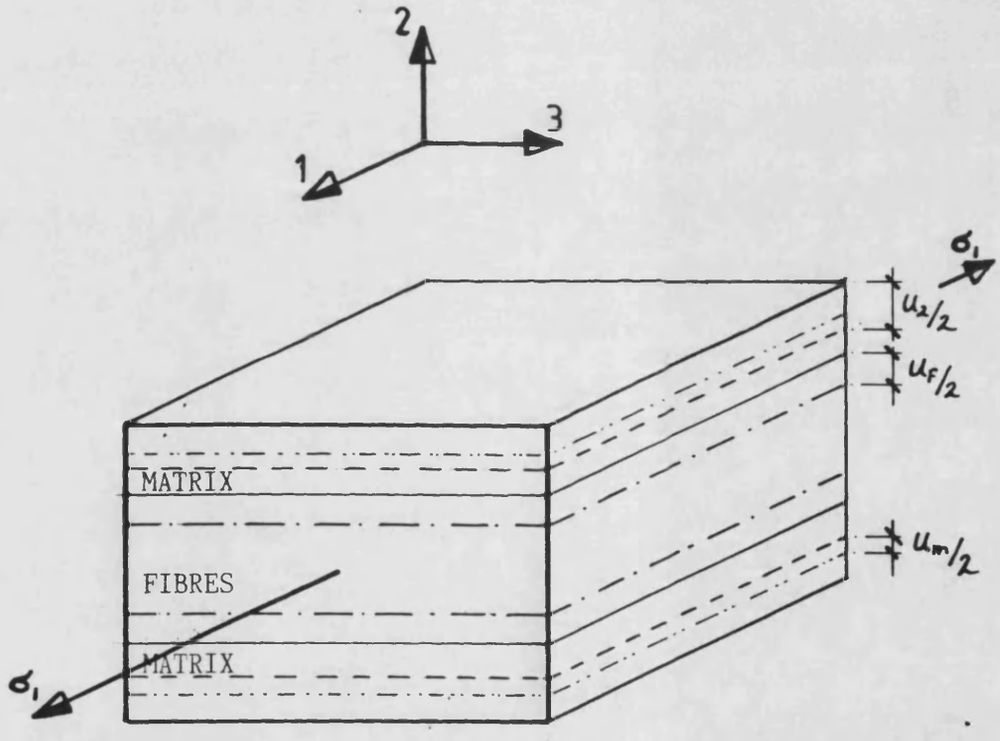


FIG. 2.8 Composite Model Showing Poisson's Shrinkage.

2.7 Elastic Stress Transfer.

The analysis so far has considered the case where composite reinforcement takes place through slip which occurs at the fibre/matrix interface.

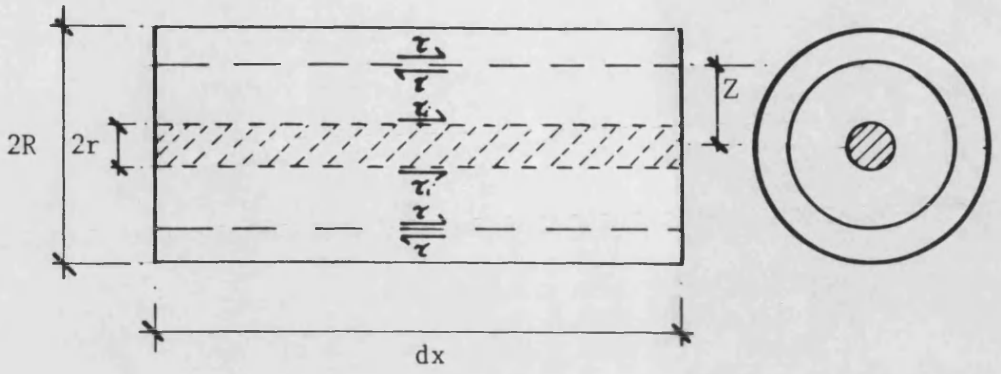
At low stresses, or when the fibre/matrix bond is good, slip may not occur. The transfer of stress from matrix to fibres in these circumstances is now considered.

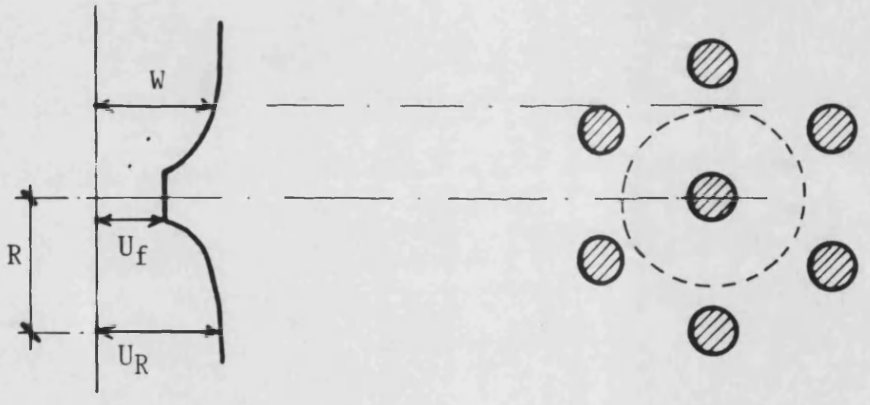
For this analysis, a composite is considered in which the fibres are arranged regularly in a square or hexagonal array. The fibres and matrix are assumed to behave elastically and the interface transfers stress from matrix to fibre without yielding or slip.

Consider a short length of a single fibre which is surrounded by matrix as shown in Fig. 2.9.

At a distance 'R' from the fibre under consideration the tensile strain in the matrix is considered to be constant. From the concept of equal strains it is assumed that this matrix tensile strain is equal to the composite strain, ie. $\epsilon_m = \epsilon_1$.

From Fig. 2.9 it can be seen that the stress distribution around the fibre has circular symmetry. The matrix dispacement 'w' and shear stress 'τ' do not vary with orientation about the fibre axis, but they are dependant upon the radial distance 'z' from the fibre centre.





Displacements along the fibre axis.

Fibres in Hexagonal array.

FIG. 2.9 Fibre Element with Surrounding Matrix.

If a cylinder of matrix is considered of radius 'z' from the fibre centre then it can be seen that the shear force on the 'surface' of this cylinder is given by the expression :

Shear Force = $2\pi z\tau\ dx$

Where τ = *shear stress at that surface*
dx = *length of the element.*

The interface shear stress between fibre and matrix is τ_i and therefore at the surface of the fibre :

$$2\pi z\tau\ dx = 2\pi r\tau_i\ dx \qquad (2.30)$$

From equation (2.30) can be derived the general expression for the shear stress in the matrix at a radius 'z' from the fibre centre :

$$\tau = r\ (\tau_i/z) \qquad (2.31)$$

If 'w' is the displacement of the matrix along the fibre axis at a radius 'z', then the shear strain is given by $^{dw}/_{dz}$ and the matrix shear modulus G_m is given by :

$$G_m = \tau/(^{dw}/_{dz}) \qquad (2.32)$$

This can be rearranged so that the shear strain is defined as :

$$dw/dz = \tau/G_m \qquad (2.33)$$

From the general expression for shear stress, equation (2.31), $\tau = r\tau_i/z$. Therefore, substituting for τ in equation (2.33) gives :

$$dw/dz = r\tau_i/zG_m \qquad (2.34)$$

If the fibre displacement at radius 'r' is U_f and the matrix displacement at radius 'R' is U_R then equation (2.34) can be rearranged and integrated such that :

$$\int_{U_f}^{U_R} dw = \tau_i r/G_m \int_r^R 1/z \, dz \qquad (2.35)$$

Therefore :

$$(U_R - U_f) = \tau_i r/G_m \ln(R/r) \qquad (2.36)$$

If 'R' is taken as the centre to centre spacing of adjacent fibres then the value of the ratio (R/r) depends upon the fibre packing arrangement. It can be shown that for a square array, $(R/r) = \sqrt{\pi/V_f}$ and that for a hexagonal array, $(R/r) = \sqrt{2\pi/\sqrt{3}V_f}$. and therefore :

$$\ln(R/r) = \tfrac{1}{2}\ln(\pi/V_f) \qquad \textit{Square Array.}$$

(2.37)

$$\ln(R/r) = \tfrac{1}{2}\ln(2\pi/\sqrt{3}V_f) \qquad \textit{Hexagonal Array.}$$

For the general case, a 'packing factor' β_f can be introduced, where the value of β_f depends upon the fibre arrangement, so that :

$$\ln(R/r) = \tfrac{1}{2}\ln(\beta_f/V_f) \qquad (2.38)$$

This expression can then be substituted for ln(R/r) in equation (2.36) to give :

$$(U_R - U_f) = \tau_i r/G_m\,[\tfrac{1}{2}\ln(\beta_f/V_f)] \qquad (2.39)$$

The shear stress at the interface between fibre and matrix is therefore given by :

$$\tau_i = 2G_m(U_R - U_f)/[r\ln(\beta_f/V_f)] \qquad (2.40)$$

It can be shown (Appendix 1)[27][28] that the shear modulus of a material is related to its elastic modulus and Poisson's ratio by the expression :

$$G = E/2(1 + v)$$

Therefore, substituting for G_m in the equation (2.40), the expression for the interface shear stress becomes :

$$\tau_i = E_m(U_r - U_f)/[(1 + v_m)r\ln(\beta_f/V_f)] \qquad (2.41)$$

From equation (2.13), it will be remembered, that the relationship between shear stress at the interface and fibre tensile stress is :

$$d\sigma_f/dx = - 2\tau_i/r \qquad (2.42)$$

If the expression for τ_i derived from equation (2.41) is substituted into equation (2.42) this becomes :

$$d\sigma_f/dx = - 2E_m(U_R - U_f)/[(1 + v_m)r^2\ln(\beta_f/V_f)] \qquad (2.43)$$

The fibre displacement is U_f, therefore, the fibre strain is given by :

$$\epsilon_f = dU_f/dx$$

And hence :

$$dU_f/dx = \sigma_f/E_f \qquad (2.44)$$

Similarly, when z = R, the strain in the matrix is given by :

$$\epsilon_m = dU_r/dx \qquad (2.45)$$

From the concept of equal strains this is equal to the composite strain ϵ_1.

Therefore, if equation (2.43) is differentiated, and substituting for dU_f/dx and dU_r/dx :

$$d^2\sigma_f/dx^2 = - 2E_m(\epsilon_1 - \sigma_f/E_f)/[(1+\nu_m)r^2 \ln(\beta_f/V_f)] \qquad (2.46)$$

This equation can be simplified by the introduction of a dimensionless paramater 'n' such that :

$$n^2 = 2E_m/[E_f(1+\nu_m) \ln(\beta_f/V_f)] \qquad (2.47)$$

Therefore, introducing this into equation (2.46) gives :

$$d^2\sigma_f/dx^2 = n^2(\sigma_f - E_f\epsilon_1)/r^2 \qquad (2.48)$$

This equation has the solution :

$$\sigma_f = E_f\epsilon_1 + B \sinh(n x/r) + D \cosh(n x/r) \qquad (2.49)$$

Where 'B' and 'D' are constants determined by the boundary conditions. If it is assumed that no stress is transferred across the fibre ends (ie $\sigma_f = 0$ when $x = L$), then $B = 0$, and $D = - E_f\epsilon_1/\cosh(ns)$, where 's' is the fibre aspect ratio.

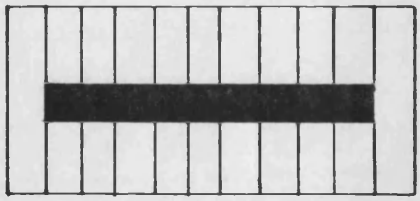
Therefore, if these boundary conditions are substituted into equation (2.49) the expression for the fibre tensile stress becomes :

$$\sigma_f = E_f\epsilon_1[1 - \cosh(n x/r)/\cosh(ns)] \qquad (2.50)$$

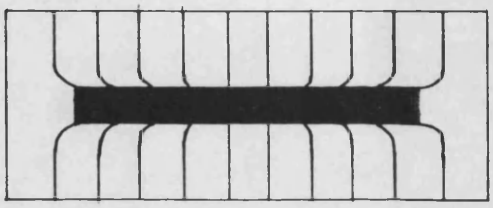
Now, as stated before, from equation (2.13), $d\sigma_f/dx = - 2\tau_i/r$. Therefore, applying this to equation (2.50) gives the following expression for the interfacial shear stress :

$$\tau_i = r/2\, E_f\epsilon_1[\sinh(n x/r)/\cosh(ns)] \qquad (2.51)$$

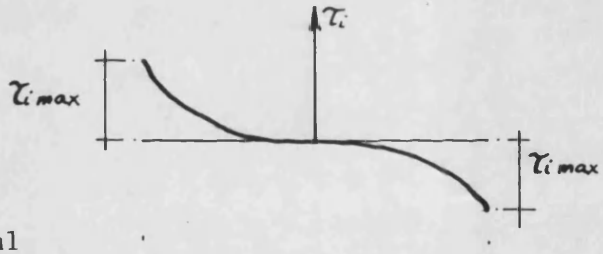
The stress distributions described in equations (2.50) and (2.51) are illustrated in Fig 2.10. This can be compared with the stress distribution when reinforcement takes place through slip which is illustrated in Fig. 2.6 .



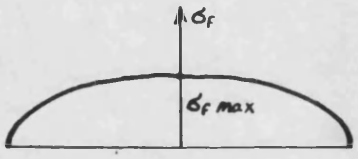
a) Unstressed.



b) Stressed.



c) Interfacial Shear Stress.



d) Fibre Tensile Stress.

FIG. 2.10 Elastic Stress Transfer.

From equation (2.6), the composite stress, σ_1, is given by :

$$\sigma_1 = V_f\sigma_f + V_m\sigma_m \qquad (2.52)$$

This is known as the **'Rule of Averages'** equation.

Therefore, in order to obtain the composite stress the mean fibre stress, $\bar{\sigma}_f$ must be first obtained by integrating equation (2.50) such that :

$$\bar{\sigma}_f = E_f\epsilon_f \int [1 - (\cosh(n^x/_r)/\cosh(ns)] \, dx$$

$$\therefore \quad \bar{\sigma}_f = E_f\epsilon_f[\, 1 - (\tanh(ns)/_{ns})] \qquad (2.53)$$

For the matrix, it is assumed that the average matrix stress, $\bar{\sigma}_m = E_m\epsilon_1$. Therefore, if the expressions for $\bar{\sigma}_f$ and $\bar{\sigma}_m$ are substituted in the 'Rule of Averages' equation (2.52). The composite stress is given by :

$$\sigma_1 = V_fE_f\epsilon_1[1 - \tanh(ns)/_{(ns)})] + V_mE_m\epsilon_1 \qquad (2.54)$$

ie. The general stress/strain relationship for the composite is :

$$\sigma_1 = \epsilon_1[V_fE_f(1 - \tanh(ns)/_{ns}) + V_mE_m] \qquad (2.55)$$

The maximum fibre tensile stress, σ_{fmax}, occurs at the mid-point of the fibre and can be derived from equation (2.50) with x = 0. Therefore :

$$\sigma_{fmax} = E_f\epsilon_1[1 - \text{sech}(ns)] \qquad (2.56)$$

This analysis is approximate, it neglects the stress transfer across the fibre ends and the stress concentrations which occur at those points. These local stress concentrations greatly increase the interface shear stress τ_i at the ends of the fibres. The end effects will however be unimportant for very long or continuous fibres with high aspect ratios.

In the case of very long or continuous fibres, the fibre aspect ratio $s \to \infty$ and equation (2.55) becomes :

$$\sigma_1 = \epsilon_1(V_fE_f + V_mE_m)$$

And once more, the composite obeys the **'Rule of Mixtures'**.

This detailed analysis of composite behaviour, both at low stresses and when slip occurs, has shown that for a composite reinforced with aligned continuous fibres the 'Rule of Mixtures' applies.

This simple set of equations for composite modulus and strength allows the composite behaviour to be easily predicted with a good degree of accuracy.

2.8 Failure Processes.

The analysis described in the previous sections models the composite behaviour at a point prior to the fracture of either the fibre or matrix component.

Types of failure in composites fall into one of two groups, either single or multiple fracture. The failure mode depends upon the relative strengths of fibre and matrix.

Single fracture occurs when, following the failure of one component, either fibre or matrix, the remaining component is unable to carry the additional load and fails as well.

Failure of the component with the lower breaking strain may not necessarily lead to total failure of the composite. If the composite stress at this point is less than the product of the strength of the remaining component and its volume fraction then this component will be able to carry the load without failing. Multiple fracture of the other component then takes place.

The conditions necessary for reinforcement to operate and for multiple fracture to take place are now discussed.

2.9 Criteria for Multiple Fracture.

The criterion for reinforcement is that the strength of the composite is greater than the strength of the matrix, ie :

$\sigma_{fult} > \sigma_{mult}$

Now, as σ_{1ult} is a linear function of the fibre volume fraction V_f there will be some positive value of V_f where :

$$\sigma_{1ult} = \sigma_{mult} \qquad (2.57)$$

This defines the critical fibre volume fraction V_{crit}.

If a composite with continuous aligned fibres is considered, then according to the 'Rule of Mixtures' :

$$\sigma_1 = \epsilon_1(V_fE_f + V_mE_m) \qquad (2.58)$$

For the case where the fibre failure strain is greater than that of the matrix, ie. $\epsilon_{fu} > \epsilon_{mult}$, and where the composite strain is equal to the matrix failure strain ($\epsilon_1 = \epsilon_{mult}$) then, substituting in equation (2.58) :

$$\sigma_1 = \epsilon_{mult}(V_fE_f + V_mE_m)$$

$$\text{or } \sigma_1 = (V_fE_f + V_mE_m)\,\sigma_{mult}/E_m \qquad (2.59)$$

This does not represent the composite failure stress, as although the matrix has cracked, the fibres can continue to take further load.

Beyond this point the matrix no longer contributes to the composite strength, and :

$$\sigma_{1ult} = V_f\sigma_{fult} \qquad (2.60)$$

So, equating $\sigma_{fult} = \sigma_{mult}$, the critical fibre volume fraction is given by :

$$V_{fcrit} = \sigma_{mult}/\sigma_{fult} \qquad (2.61)$$

If this is applied to a carbon fibre/cement composite for example, where the typical component properties are:

σ_{mu} = 5.0 N/mm^2 (say)

σ_{fu} = 3000 N/mm^2 (say)

Then the critical fibre volume fraction is given by :

V_{fcrit} = 5/3000 = 0.0017 (0.17 %)

This is very low and is equivalent to approximately 1 tow of carbon fibre per 250mm^2 of cement matrix.

It should be noted that no critical fibre volume fraction exists for stiffening. Provided that $E_f > E_m$ stiffening will occur at all volume fractions.

It can be seen from equations (2.59 & 2.60) that for multiple fracture of the matrix to occur :

$$V_f\sigma_{fult} > (V_fE_f + V_mE_m)\sigma_{mult}/E_m \qquad (2.62)$$

2.10 Multiple Matrix Fracture.

Multiple fracture is a progressive process which is controlled by the presence of flaws in the matrix. The first crack in the matrix will occur at the most serious flaw. The matrix on either side of this crack, has less serious flaws and is therefore stronger, so a greater stress is required to cause failure.

The next matrix crack will occur at the next largest flaw and so the process continues until the pieces of matrix remaining are too small to allow the fibres to transmit the necessary breaking stress to them.

To analyse the fracture processes a number of assumptions are necessary :

1) Elastic stress transfer is neglected.

2) Stress transfer takes place by friction at the interface at a constant shear stress τ_i

3) Matrix strength is assumed initially to be constant.

Before the first crack occurs in the matrix, it can be seen, from consideration of equilibrium, that :

$$\sigma_1 = V_f\sigma_f + V_m\sigma_m \qquad (2.63)$$

It will be recalled, from the equal strain assumption, that the composite strain is equal to the fibre strain and the matrix strain, such that $\epsilon_1 = \epsilon_f = \epsilon_m$

The stress/strain relationship of the composite is therefore given by $\sigma_1 = E_1\epsilon_1$ where :

$$E_1 = V_f E_f + V_m E_m \qquad (2.64)$$

As the composite stress is increased, the stress in the matrix approaches the matrix strength, such that the first matrix crack appears when :

$$\sigma_1 = V_f \sigma_f + V_m \sigma_{mult} \qquad (2.65)$$

Further increase in composite strain generates further cracks in the matrix. The stress distributions during multiple matrix fracture in a composite containing continuous, aligned fibres are illustrated in Fig. 2.11.

From this it can be seen that between the matrix cracks three distinct stress regions exist. Away from the cracks, in the centre region of the piece of matrix, no slip occurs at the fibre/matrix interface and the fibre and matrix stresses are constant with values of σ_{f1} and σ_{m1} respectively.

Near each crack, slip is taking place over a length 'mL_m' and by equating the interfacial shear force and the fibre tensile force, (see eq (2.12) & (2.13)), it can be seen that :

$$d\sigma_f/dx = 2\tau_i/r \qquad (2.66)$$

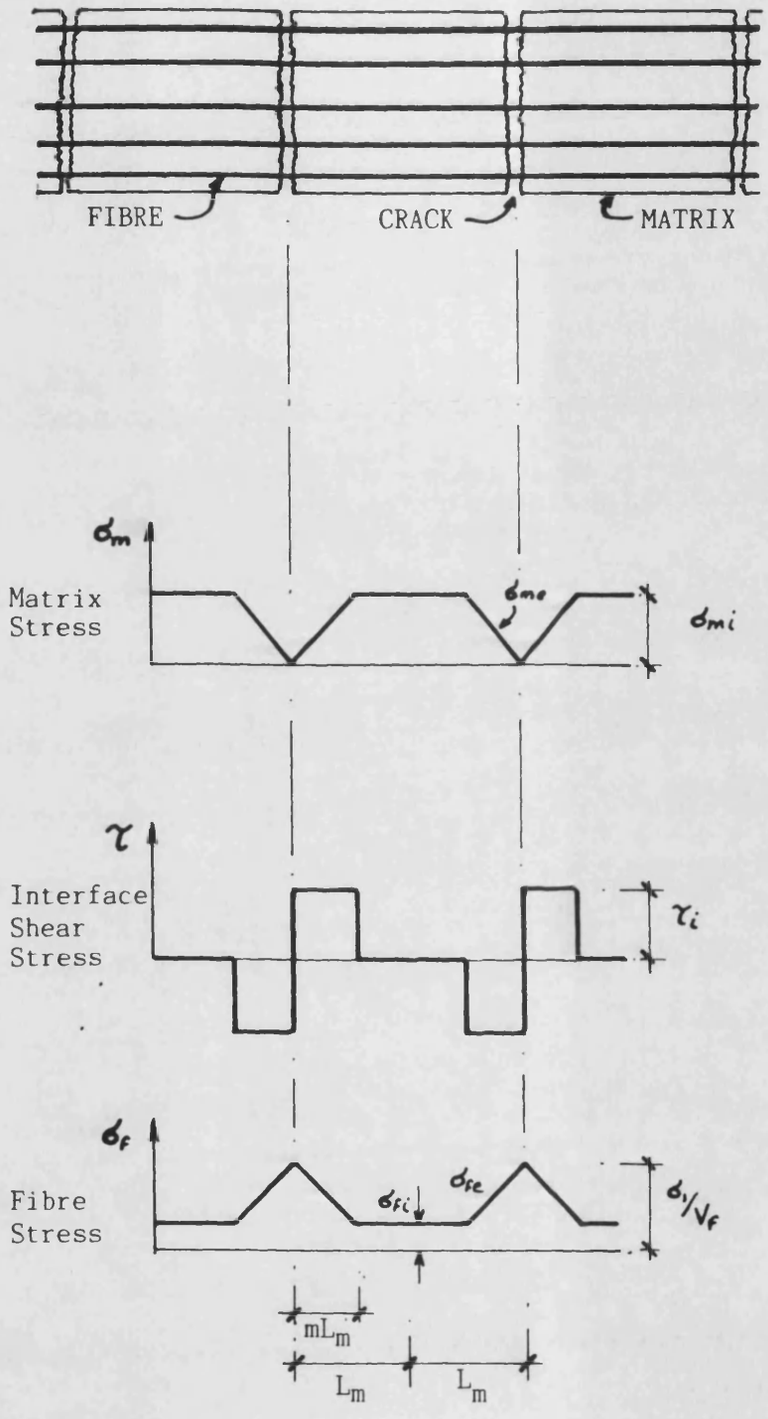


FIG. 2.11 **Stress Distribution During Multiple Fracture of the Matrix.**

If equation (2.66) is integrated with the boundary condition $\sigma_1 = V_f\sigma_f$ at $x = L_m$, ie the matrix stress is zero at the crack, then the fibre stress in the slip zone is given by :

$$\sigma_{fx} = \sigma_1/V_f - 2\tau_i/r(L_m - x) \qquad (2.67)$$

But at the point where the slip zone ends, ie. $x = L_m(1 - m)$, the fibre tensile stress $\sigma_{fx} = \sigma_{fi}$, therefore, substituting in eq. (2.54):

$$\sigma_{fi} = \sigma_1/V_f - 2\tau_i m S_m \qquad (2.68)$$

Where the matrix aspect ratio, $S_m = L_m/r$

It will be recalled from eq. (2.63) that $\sigma_1 = \sigma_f V_f + \sigma_m V_m$. Therefore, if $\sigma_f = \sigma_{fi}$ and $\sigma_m = \sigma_{mi}$ and these values are substituted into equation (2.63), then the stress in the matrix, σ_{mi}, over the centre region, where no slip occurs, can be obtained by substituting for σ_{fi} from eq. (2.68) into eq. (2.63) to give :

$$\sigma_{mi} = 2V_f\tau_i m S_m/V_m \qquad (2.69)$$

When a new matrix crack is formed there will be a marked fall in the applied stress. As the composite strain further increases the applied stress will gradually increase again as the slip regions develop either side of the new crack position.

The matrix will crack again when the stress induced in the matrix reaches a value equal to the matrix strength, ie. when $\sigma_{mi} = \sigma_{mult}$. In this case, the proportion of the length of the matrix unit over which slip occurs 'm' reaches a critical value, such that $m = m_{crit}$.

Therefore by substituting $m = m_{crit}$ in eq. (2.69) and rearranging, it can be seen that :

$$m_{crit} = V_m\sigma_{mult}/2V_f\tau_i S_m \qquad (2.70)$$

The composite stress is once again given by eq. (2.65), ie. $\sigma_1 = \sigma_f V_f + \sigma_{mult}V_m$.

As each new crack forms, the matrix aspect ratio, 'S_m' decreases to half of its previous value. This process can only continue until $m_{crit} = 1$. When this value is reached then slip occurs along the full embedded fibre length. From eq. (2.70) the matrix aspect ratio when this occurs is given by :

$$S_m = V_m\sigma_{mult}/2V_f\tau_i \qquad (2.71)$$

The smallest theoretical value of S_m is therefore half of this ie.

$$S_{min} = V_m\sigma_{mult}/4V_f\tau_i \qquad (2.72)$$

In practice this minimum matrix aspect ratio is unlikely to be reached and the matrix will break into blocks having lengths between $2rS_{min}$ and $4rS_{min}$.

While cracks are still being formed, in the centre region of each matrix block, no slip is taking place at the fibre/matrix interface and the fibre and matrix strains are the same.

Therefore, at the instant a new crack is formed, the fibre stress is given by :

$$\sigma_{fi} = \sigma_{mult} E_f / E_m \qquad (2.73)$$

If this is substituted into equation (2.65), the composite stress is given by :

$$\sigma_1 = V_f \sigma_{mult} E_f / E_m + V_m \sigma_{mult} \qquad (2.74)$$

Rearranging this gives :

$$\sigma_1 = \sigma_{mult} [V_f (E_f / E_m) + V_m]$$

From the 'Rule of Mixtures', $E_1 = V_f E_f + V_m E_m$, therefore, the composite stress when a new crack is formed is given by :

$$\sigma_1 = \sigma_{mult} E_1 / E_m \qquad (2.75)$$

It can be seen from eq. (2.75) that the composite stress necessary to cause matrix cracking is thus constant.

The total composite displacement is equal to the total fibre displacement, therefore the strain in the composite can be derived from the average fibre strain ie. $\epsilon_1 = \epsilon_f$.

If a block of matrix between two cracks is considered, the fibre displacement U_f is given by :

$$U_f = 1/E_f \int \sigma_{fi}\, dx + 1/E_f \int \sigma_{fe}\, dx \qquad (2.76)$$

The average fibre strain is given by : $\bar{\epsilon}_f = U_f/L_m$ thus, if σ_{fi} is substituted from eq. (2.68), Equation (2.76) can be integrated and divided by L_m to give the expression for composite strain :

$$\epsilon_1 = 1/E_f \left[(\sigma_1/V_f) - 2\tau_i m S_m (1 - m/2) \right] \qquad (2.78)$$

When a new matrix crack appears and $m = m_{crit}$, equation (2.78) can be used to give a series of values of ϵ_1 which increase as the matrix aspect ratio S_m decreases. Therefore, putting $m = m_{crit}$ and using the expression derived for m_{crit} in equation. (2.70). and the expression derived for σ_1 in eq. (2.75) it can be seen that :

$$\epsilon_1 = \epsilon_{mult} [1+ (V_m^2 \sigma_{mult} E_m/4V_f^2 \tau_i S_m E_f) \qquad (2.79)$$

Matrix cracking ceases when the matrix aspect ratio S_m becomes less than $2S_{min}$. So by substituting for $2S_{min}$ using eq. (2.72) the value of composite strain ϵ_{1max} at which the region of constant stress ends is given by:

$$\epsilon_{1max} > \epsilon_{mult}(1 + V_m E_m/2V_f E_f) \qquad (2.80)$$

As the crack spacing cannot be less than S_{min}, the upper bound value for ϵ_{1max} is :

$$\epsilon_{1max} < \epsilon_{mult}(1 + V_m E_m / V_f E_f)$$

Therefore, the limit of the constant stress region during which matrix cracking takes place is defined by :

$$\epsilon_{mult}(1 + V_m E_m / 2V_f E_f) \leq \epsilon_{1max} \leq \epsilon_{mult}(1 + V_m E_m / V_f E_f) \qquad (2.81)$$

Any further increase in composite strain does not affect the matrix. Beyond this point, the composite properties become proportional to the properties of the fibres such that the slope of the stress/strain graph becomes $E_f V_f$ and the composite finally fails when $\sigma_1 = V_f \sigma_{fult}$.

The composite stress/strain behaviour described here is illustrated in Fig 2.12 . From this it can be seen that the curve of the stress/strain graph has three distinct gradients.

The initial slope in the low stress region 'OA' has the gradient E_1 and ends where multiple cracking of the matrix begins. ie. when the composite strain $\epsilon_1 = \epsilon_{mult}$.

The constant stress region 'AB' represents the zone of multiple matrix fracture and the many small peaks and troughs represent the formation of cracks. This zone ends when the composite strain reaches ϵ_{1max} as defined by equation (2.81)

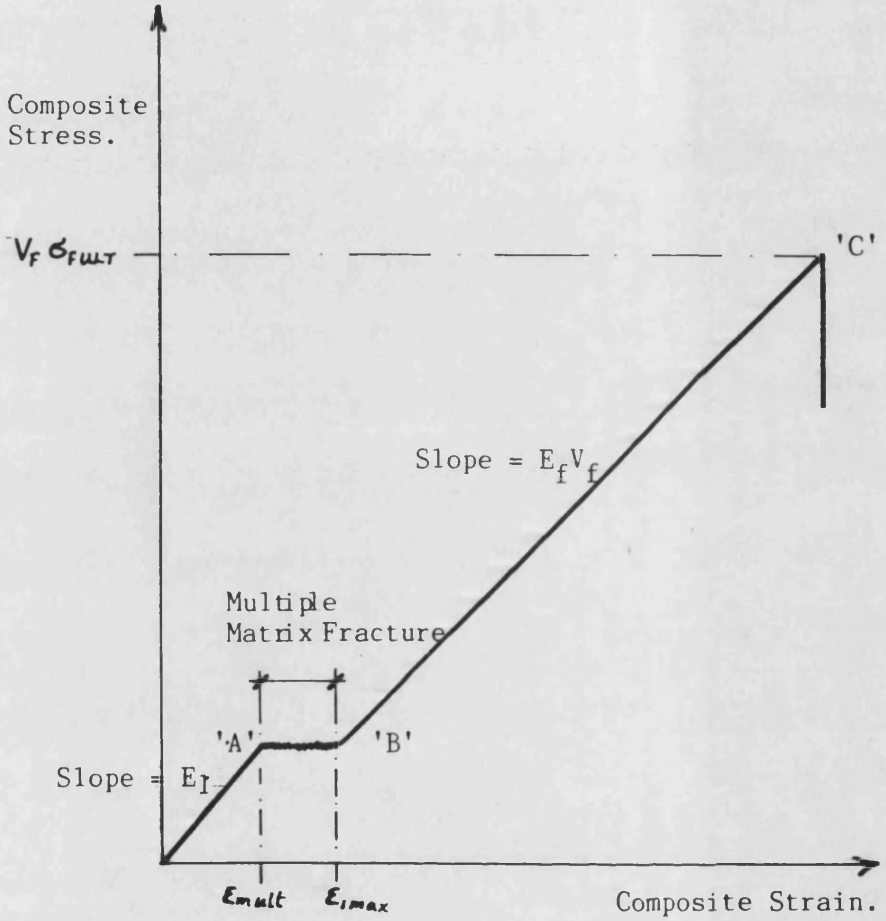


FIG. 2.12 **Typical Stress/Strain Curve for a Fibre Reinforced Composite.**

Although the section of the graph 'AB' has been referred to as a 'constant stress' region, it will in reality have a slight positive gradient. This is due to the increasing strength of the matrix as it breaks into smaller pieces and the matrix aspect ratio S_m decreases. As mentioned earlier each crack removes the most serious flaw so the remaining matrix is stronger.

The length of this region is proportional to $V_m E_m / V_f E_f$ and is therefore a function of the fibre and matrix combination used.

The third section of the graph is related only to the fibre properties, has a slope $V_f E_f$ and ends at the breaking stress of the fibres, when $\sigma_1 = \sigma_{fult} V_f$

CHAPTER THREE

Carbon Fibre Reinforced Cement

3.1 Introduction.

This chapter makes a detailed analysis of carbon fibre reinforced cement and consists of two parts.

The first part considers the component materials individually, it studies their history, manufacture and properties. The second considers the combination of the components to form a composite material and examines the pros and cons of this combination.

3.2 Carbon Fibres.

Carbon fibres are produced by the carbonisation of a fibre precursor. The properties of the resulting fibre depend to a large extent upon the properties of the original precursor.

Many precursors have been tried over the years with varying degrees of success. Of these, three main types are used as the basis of carbon fibres being produced today. These are Polyacrylonitrile (known as 'PAN'), Rayon and Pitch.

Pitch fibre precursors are mainly used in Japan and have the advantage of being fairly cheap, but their mechanical properties are not as great as some of the alternatives. They are ideal however for the production of low modulus carbon fibres and textiles.

Rayon, which is a cellulose fibre, is one of the most widely used precursors. It is used particulary by 'Union Carbide' in the USA in the production of their 'Thornel' carbon fibre.

In Rayon based carbon fibres the graphite layers tend to be preferentially orientated parallel to the fibre axis, this is largely derived from the preferred orientation present in the precursor fibre.

The alignment of the crystals in the fibres is of great importance with respect to the modulus and it has been found that the greater the degree of moleculor orientation the greater the tensile modulus.

Bacon and Schalamon [29] found that by 'hot working' the fibres, ie. by stretching them during the carbonisation process, it was possible to obtain great improvements in both strength and modulus. As the graphite crystals became more closely aligned to the fibre axis the fibre modulus improved sharply.

The Polyacrylonitrile 'PAN' precursor, commonly used in this country, has a significant advantage over Rayon in that it has a high degree of moleculor orientation. This enables the production of carbon fibres which have a high tensile modulus. An additional advantage is that Polyacrylonitrile gives much greater yields than Rayon, typically over 50% compared to 30% for Rayon.

Some of the earliest work on PAN based carbon fibres was carried out by Akai Shindo [30] in Japan who showed that carbon fibres having a tensile modulus of as high as 165 x 10^3 N/mm^2 could be produced and that these had an appreciable degree of preferred orientation. This was achieved without stretching of the fibres during manufacture.

Watt, Phillips and Johnson [31] working at the Royal Aircraft Establishment at Farnborough saw the potential of the PAN precursor and set out to develop carbon fibres having very high strength and stiffness.

The essential feature of their work was that they introduced a preliminary oxidation stage. during which the fibres were held in tension while they were heated to 200 - 250°C. This modified the PAN structure, ensuring that the carbon chains were well aligned, which resulted in an improved product after the subsequent carbonisation.

The moleculor structure of the Polyacrylonitrile fibre is in the form of long chains as shown in Fig. 3.1 . These chains are fully repetitive and contain CN groupings which have a triple valency bond and are therefore very active.

When PAN is heated, the moleculor structure changes and a ladder polymer consisting of six membered groups is formed as is illustrated in Fig 3.2.

The ladder polymer is more stable towards heat than the original chain and therefore does not melt easily. This explains why PAN is suitable for conversion into carbon fibre by heat treatment.

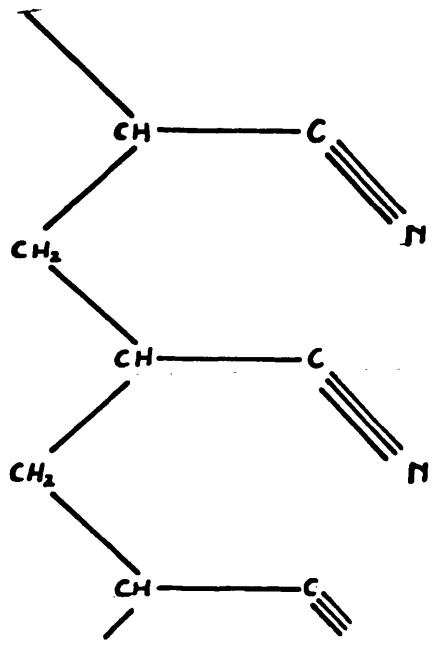


FIG. 3.1 Moleculor Structure of a Polyacrylonitrile Fibre.

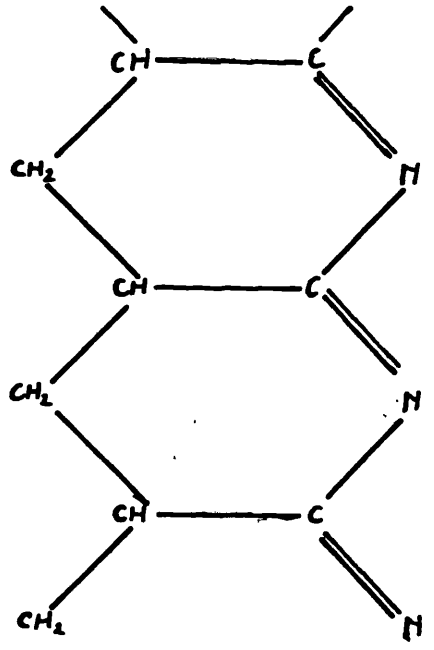


FIG. 3.2. A Ladder Polymer.

As PAN is heated above 80°C the moleculor chains start to shrink, the chains also become distorted and bend and twist in the fibre structure so that the orientation is lost. However, if tension is applied during heating the moleculor chains are prevented from shrinking and their orientation is preserved.

If Pan is heated in an oxidising atmosphere to about 220°C a chemical reaction takes place in which oxygen is taken up into the fibre as illustrated (simply) in Fig 3.3.

The take up of oxygen is associated with the formation of good chemical cross-links which firmly bond the moleculor chains together. Since the CN groups can be orientated at different angles, several moleculor chains can be tied together by the oxygen bond.

During carbon fibre manufacture the important feature is the formation of strong oxygen cross links. The effect of these links on the moleculor chains of PAN is illustrated in Fig. 3.4.

The oxidation of PAN under tension, which Watt and his colleagues introduced, therefore allows the formation of the oxygen cross-links between the moleculor chains. Hence the chains remain straight and orientated parallel to the fibre axis even when all tension is removed at the end of heating.

Subsequent carbonisation of the 'oxidated' fibres produces a carbon ring structure as shown in Fig. 3.5.

Carbon fibres therefore owe their strength to the covalent carbon-carbon bond as illustrated in Fig. 3.6

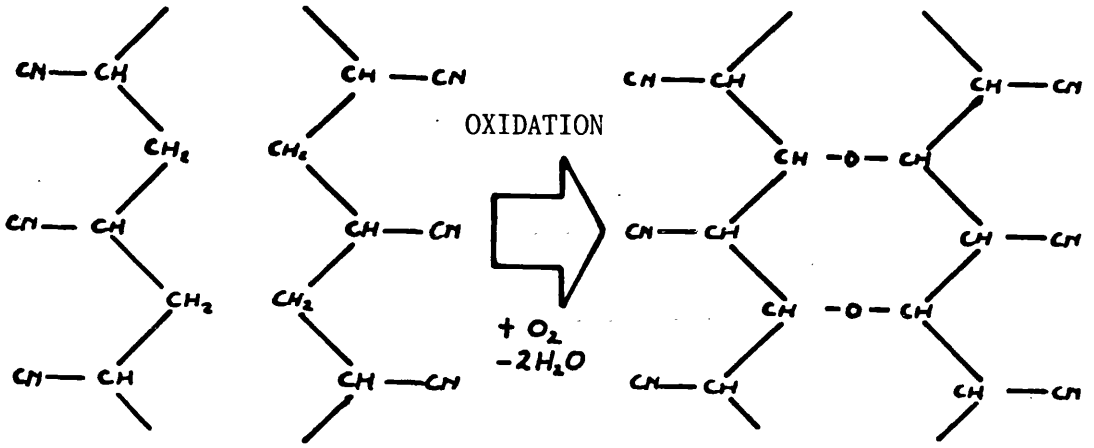


FIG. 3.3 Oxidation of PAN.

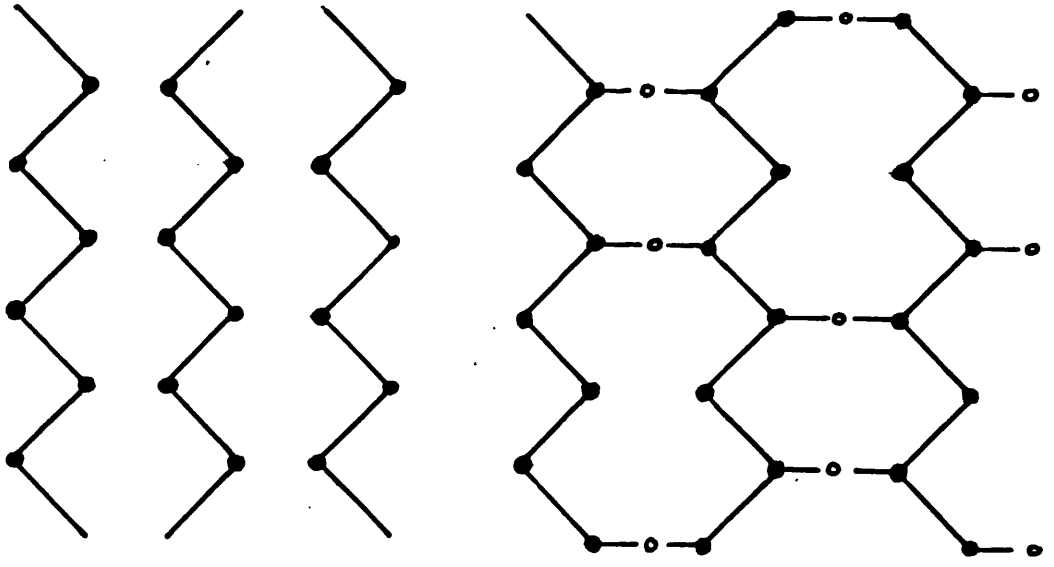


FIG. 3.4 Oxygen Cross-Links.

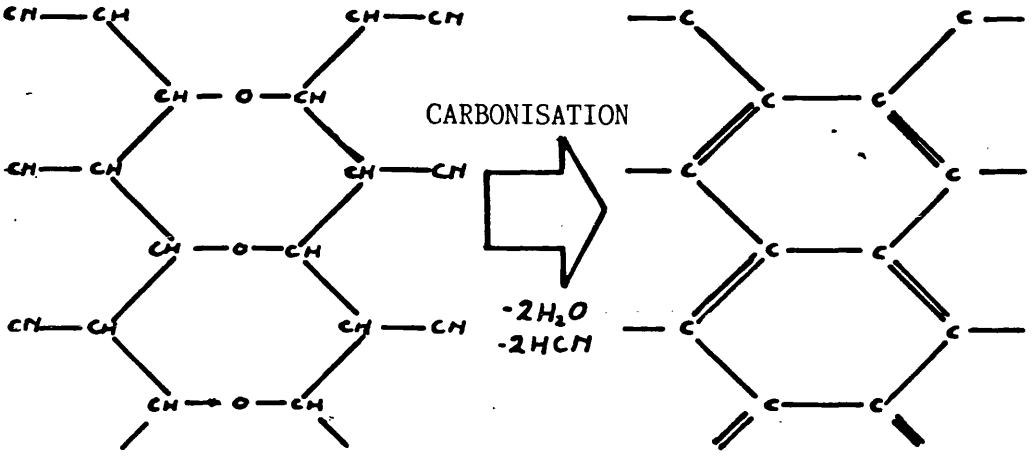


FIG. 3.5 Carbon Ring Structure.

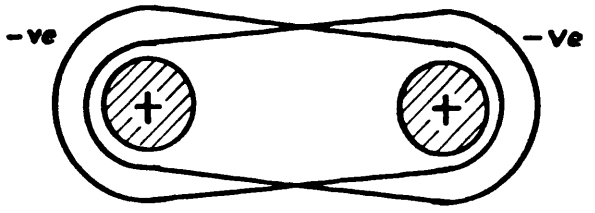


FIG. 3.6 Covalent Carbon-Carbon Bond.

A covalent bond occurs when two atoms come together and the electron of one becomes involved with the ion of the other. The total energy of the pair of atoms is reduced by this sharing and the resultant molecule is much more stable than the single atoms. This is a highly directional bond because of the tendancy of the electron clouds to align themselves along the axis of the molecule. This alignment resists changes in shape.

Carbon fibre produced from PAN precursor has a fine and well orientated crystal structure which is responsible for its high strength and relatively high modulus. Graphitisation of the carbonised fibre increases the modulus even further.

The graph in Fig. 3.7 illustrates how the fibre properties vary, depending upon the temperature of the heat treatment applied.

The tensile strength increases with temperature upto approximately 1500°C when a maximum value of about 3400N/mm^2 is achieved. Above this temperature the strength gradually falls off until 2200°C is reached, Further increase in temperature has no significant effect upon the tensile strength. The tensile modulus on the other hand shows a steady increase as the temperature is raised.

From this it can be seen that by carefully selecting the temperature of the manufacturing process, it is possible to produce fibres which have almost any combination of desired properties. The limitation to this is that the higher modulus fibres will have lower strengths due to the fall off in strength associated with the higher process temperatures.

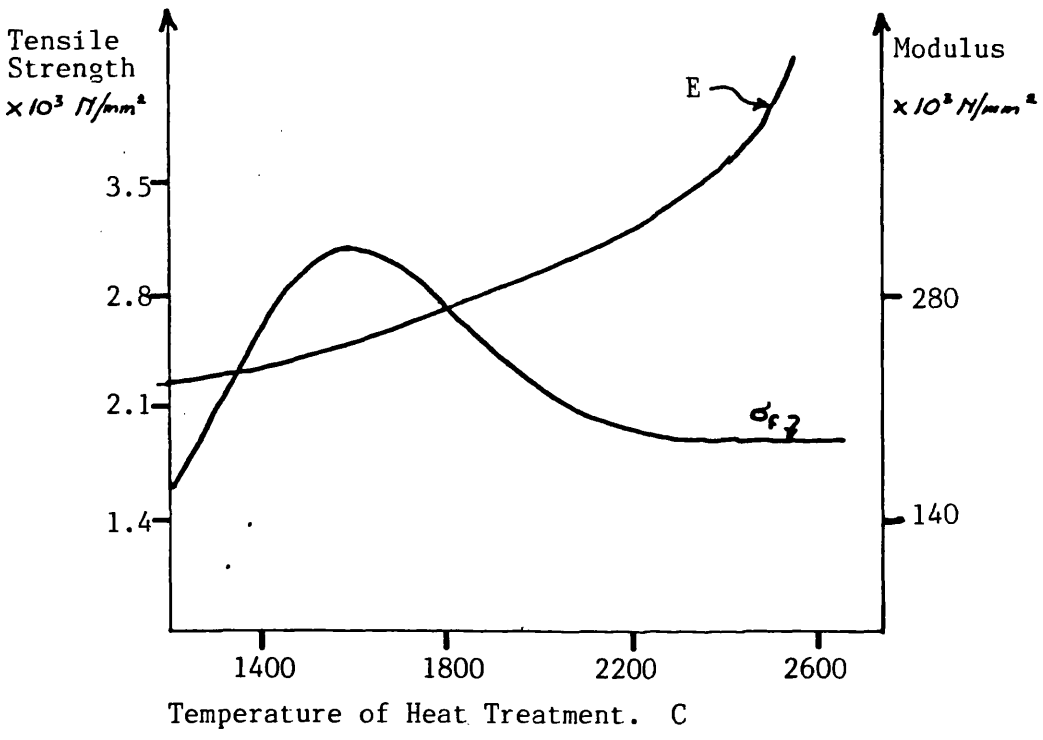


FIG. 3.7 Variation of Fibre Properties.

3.3 Fine Structure of PAN Based Carbon Fibres.

Several workers [32][33] have concluded that carbon fibres are made up of elongated or needle shaped structural units called crystalites or fibrils. It is believed that these fibrils may be bonded together by a secondary carbon phase.

The fibrils themselves are composed of graphite plates which lie in random directions. However in the case of high modulus fibres, the orientation is greater and the axis of the fibrils is less than ten degrees from that of the fibre.

It is assumed that these fibrils result from the breakdown of the structure of the PAN precursor. Therefore, although little is known about the length of the fibrils it is likely that the fibril length is related to the length of the polymer chain in the precursor.

Johnson and Tyson[34] found that the fibrils had widths of 50 - 100Å and lengths over 1000Å and they postulated a schematic diagram showing the likely carbon fibre structure. This is illustrated in Fig. 3.8.

The structure is based on tetragonal crystals having a slight misorientation and enclosing sharp edged voids or pores.

The nature of the interface between adjacent crystals is not fully understood, but it is believed that a fine non-crystaline structure exists.

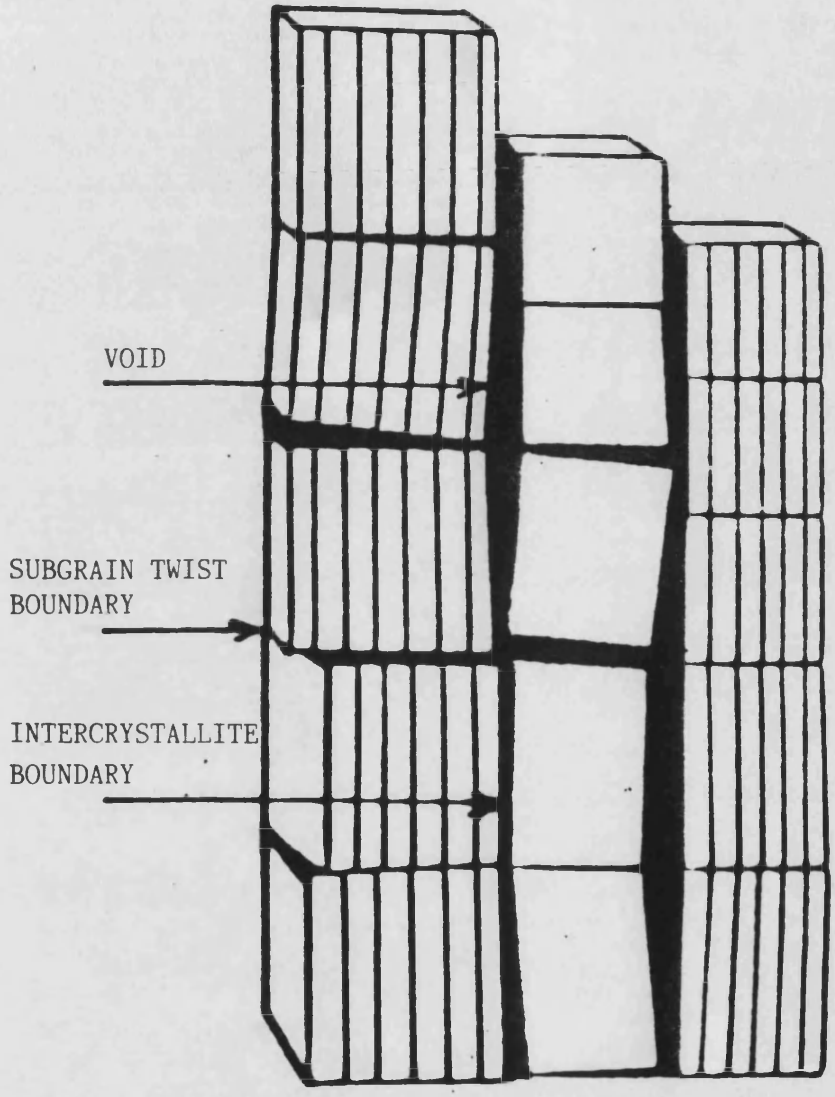


FIG. 3.8 Carbon Fibre Structure.

Johnson and Tyson believe that stretch-graphitised fibre has increased strength and stiffness due to a removal of voids and also as a result of the reduction of lattice defects.

3.4 Relationship Between Length and Strength.

The strength of a carbon fibre, determined from tensile tests is dependant upon the gauge length of the fibre under test. Long fibres have lower strengths than short ones.

It is possible that the relationship between gauge length and breaking strength gives some evidence to the existence throughout the fibre of end to end joints or bonds between the fibrils. On average the fibrils will be butt jointed in a random fashion so that at any cross section there will be some fibrils and some joints.

At some points along the length of a fibre the number of joints will be above average creating a weak plane normal to the fibre axis. This will result in reduced fibre strength at that point. Consequently, the longer a fibre, the higher is the probability of a weak plane occurring.

As an analogy consider a chain, the strength of which is determined by the strength of the weakest link. The longer the chain, the more links and the higher the probability that it includes a weak link. A long chain will therefore, on average, have a lower strength than a short one.

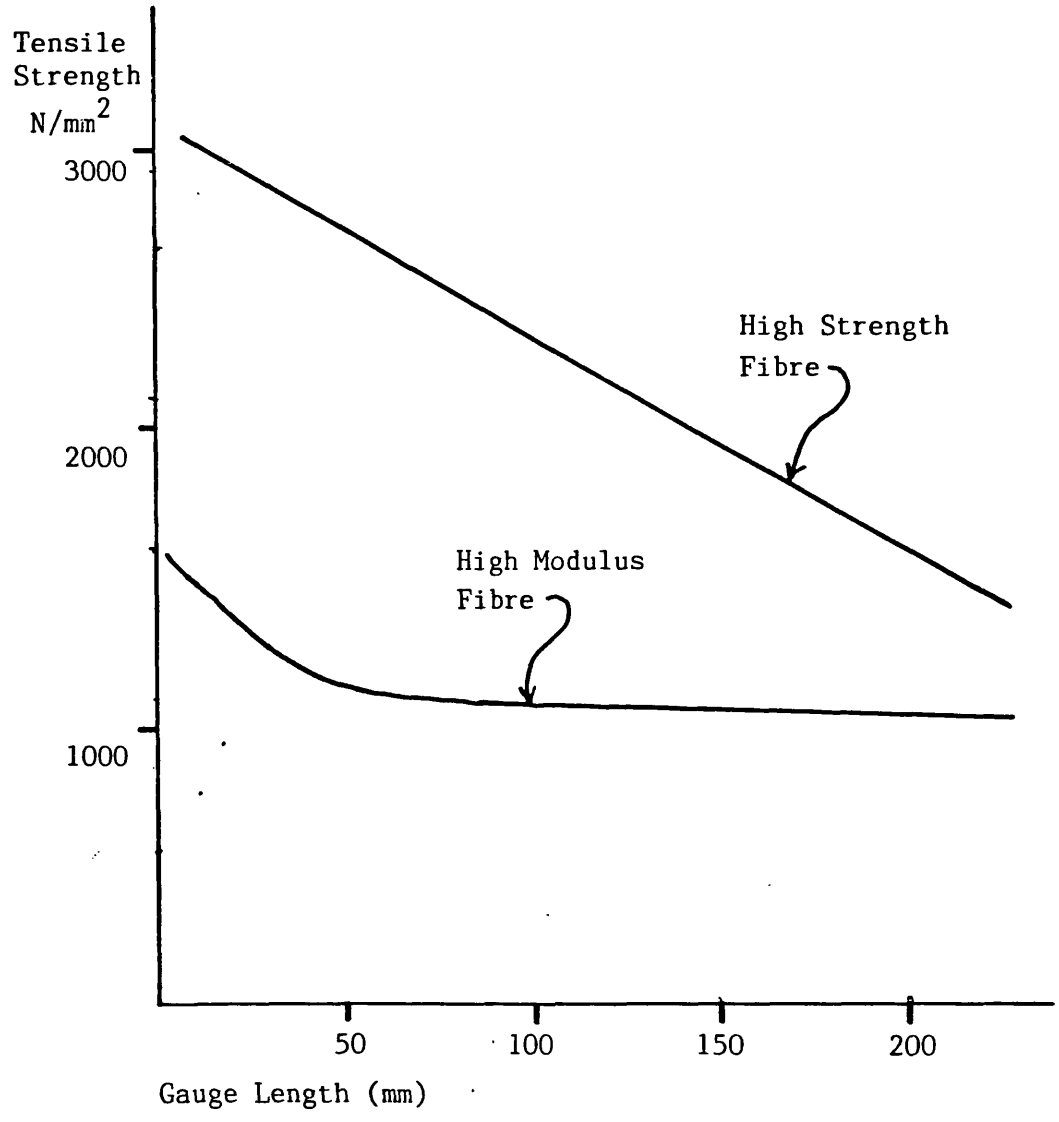


FIG. 3.9 Relationship Between Fibre Strength and Length.

A typical relationship between fibre strength and fibre length is shown in Fig. 3.9. It can be seen from this that the tensile strength of the fibre is still falling off at 200mm which suggests that longer lengths will have even lower strengths.

This length 'dependancy' is one reason why it is not possible to make economic use of carbon fibres on their own, as, for example, in a rope. The tensile strength of such a rope would be lower than the tensile strength of the fibres would suggest. As the weaker fibres break load would be transferred into the remaining fibres, making failure in those more likely.

When fibres are incorporated into a composite the stresses are redistributed around the fibre breaks by the matrix. This allows the unbroken length to continue to carry load. Because the fibre will fail at its weakest point first, the remaining lengths of the fibre either side of the break will be stronger than the whole fibre was before the break.

3.5 Manufacture of High Modulus Carbon Fibres From 'PAN' Precursors.

The processing of Polyacrylonitrile precursors to produce high modulus carbon fibres is carried out in four main stages. The properties of the resulting fibres are determined by the temperatures reached during manufacture.

The four stages of fibre manufacture are :

a) Oxidation
b) Carbonisation
c) Graphitisation
d) Surface Treatment

The manufacturing process is illustrated diagramatically in Fig. 3.10.

The raw material - Polyacrylonitrile in the form of a copolymer, consists of very fine filaments. Usually 6,000 - 12,000 individual filaments are included in each fibre yarn or 'tow'.

The various stages of the manufacturing process are now described.

a) Oxidation.

This takes place at temperatures in the range 200 - 250°C. The application of tension to the fibres keeps the moleculor chains stretched and parallel to the fibre axis.

During oxidation of the precursor an exothermic chemical reaction takes place and toxic gases are released. Because of the danger from these toxic gases oxidation plants must be designed to prevent gas leakage.

Any form of heat source could be used at this stage, for example, gas or electricity. However, good temperature control is essential, together with free circulation of air to achieve uniform oxidation of the precursor.

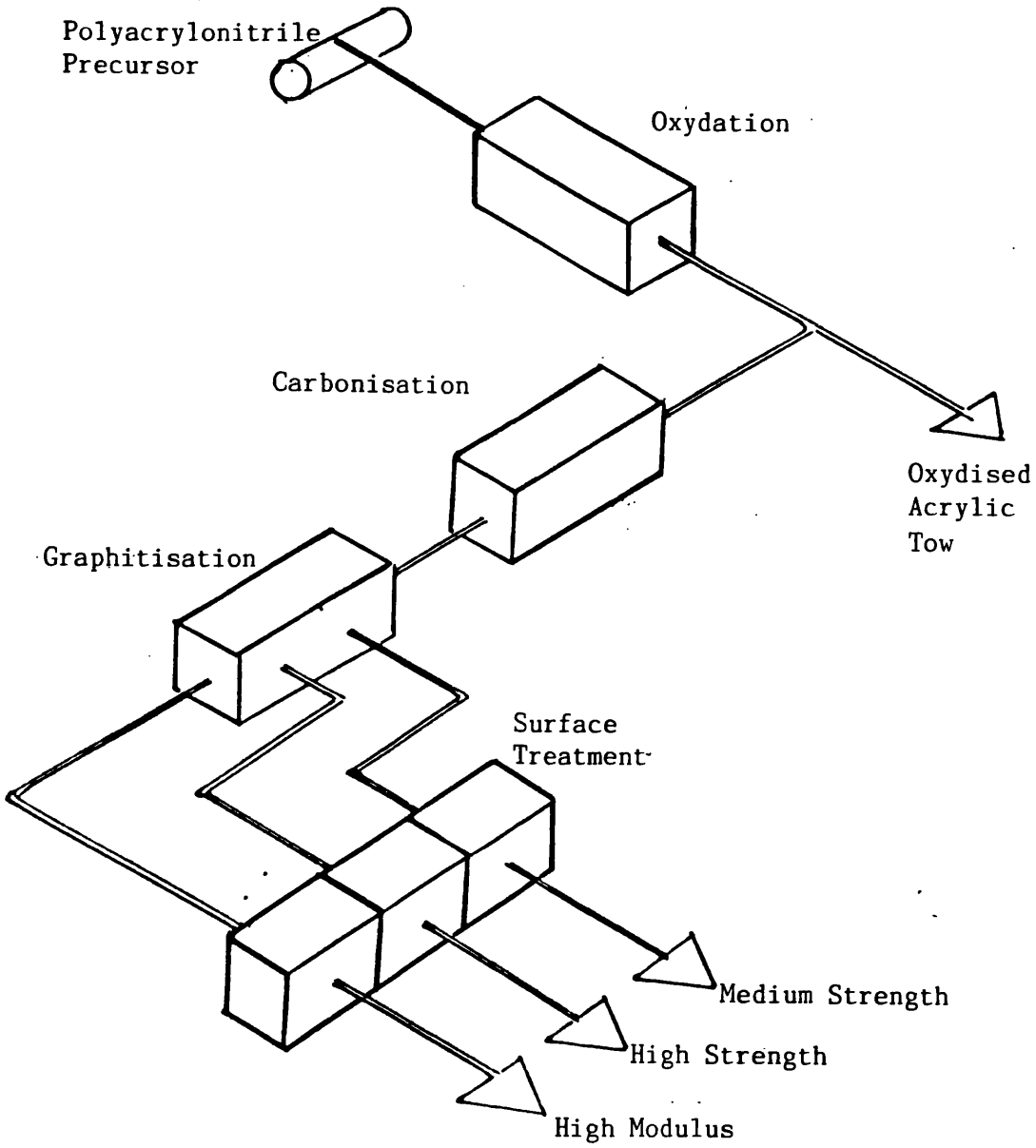


FIG. 3.10 The Production of 'PAN' Based Carbon Fibre.

At the end of this stage the resulting fibres possess exceptional thermal resistance properties and yet retain their textile character. The fibres have a laddered polymer structure which is highly heat resistant and which will not melt[35].

These properties make the fibres ideal for use in thermally protective products such as fire protective screens, blankets, clothing and upholstery[36]. The need for such fire resistant materials, particularly in the aircraft industry, where people are now more aware of the potential dangers, is growing rapidly.

b) Carbonisation.

During this part of the process, the fibres are kept out of contact with air. An inert atmosphere of nitrogen or argon gas is normally used in the furnaces.

Heating in the carbonisation plant can be by electric, gas or oil burners and maximum temperatures in the range 1000 - 1500 °C are attained.

At this stage the change from an organic fibre to carbon takes place. Weight loss of upto 50% may occur as volatiles and tarry substances are given off.

Care has to be taken to ensure that the release of volatiles, which have to diffuse from the centre of the fibre to the surface, does not damage the fibre.

The volatiles which are given off at this stage are also toxic and they must be dealt with safely.

Most of the volatiles are released before 1000°C is reached but traces of organic carbon rich residues remain until 1400 - 1500°C

During this process the fibres shrink, both in diameter and length. The bulk of these dimensional changes takes place at temperatures upto 800°C.

High strength carbon fibres result from carbonisation in the range 1100 - 1500°C. The material then consists of very small crystals which have good orientation, but there is still some porosity in the fibres.

c) Graphitisation.

The graphitisation stage is necessary for the production of high modulus fibres.

Electrically heated furnaces are invariably used and process temperatures of upto 3000°C are involved.

The complete exclusion of air is required as even minute traces could reduce the fibre properties and an inert atmosphere is a necessity. Argon is commonly used, though helium is an alternative. Unlike at the carbonisation stage, nitrogen cannot be used since at temperatures over 2000°C this will rapidly react with the carbon to form cyanogen.

Heating rates at this stage can be fairly rapid as there are no volatiles to remove and development of the graphite structure in carbon takes place very quickly.

Depending upon the degree of graphitisation a family of carbon fibres can be produced having varying properties according to user requirments.

d) Surface Treatment.

This is the final stage in the production process. Surface treatment has been found to be necessary because it is difficult to obtain a good bond between carbon fibres and matrix materials. This is a particular problem because the structure of high modulus fibres is essentially graphitic presenting a poor bonding surface to the matrix.

Bonding can be improved by surface treating the fibres. A number of methods have been developed in which solutions such as nitric acid, acetic acid or sulphuric acid are used.

Exactly what takes place is uncertain, but some degree of chemical cleaning occurs, together with some degree of etching, all of which assist in improving adhesion.

Surface treatment does not involve the application of any surface film or coating.

These processes have been developed to improve the bond with thermosetting resins, it is likely therefore that other processes may be required for alternative matrices such as cement paste.

3.6 The History of Cement.

Cement and concrete have been used in the construction industry since the earliest days. The Romans made good use of a concrete based on hydrated lime in the construction of many buildings including the magnificent Pantheon which was built around 120 AD and is still standing today.

The skill of making good concrete was lost after the Romans and was not rediscovered until more modern times.

The modern development of hydraulic cements really began towards the end of the eighteenth century when Smeaton[37] discovered that if limestone containing clay was calcined, it gave a lime which hardened under water.

This was not cement as it is known today, and it was not until 1824 that Joseph Aspdin patented a 'Portland' cement made by burning chalk with clay and grinding the sintered product. Although this is an ancestor of modern portland cement it was a much inferior product. It was not until higher burning temperatures and the addition of gypsum were introduced at the end of the 19th century that the product became more closely related to the cement used today.

Since then, quality control has greatly improved and cements having consistently good properties can now be produced.

The name 'Portland' cement is said to derive from its colour which is similar to the grey stone quarried at Portland on the South coast.

3.7 Manufacture of Portland Cement.

The raw materials from which portland cement is made are limestone or chalk for calcium carbonate, and clay or shale for silica, alumina and iron oxide.

The process of manufacturing portland cement can be broken down into eight distinct stages :

1) The raw materials are reduced by grinding to a fine particle size so that they can be intimately mixed.

2) The raw materials are blended and mixed to produce a raw 'feed' mix of uniform chemical composition containing calcium carbonate, silica, alumina, iron oxide and other compounds in the required proportions.

3) The blended raw mix is heated to the point where all moisture is driven off as steam or water vapour.

4) The dried mix is then further heated to decarbonisation or calcining temperatures of about 800°C. At this temperature the calcium carbonate in the mix is dissociated into calcium oxide (free lime) which remains in the mix and carbon dioxide which is driven off as a gas.

5) Further heat is applied, and as the temperature rises the oxides of calcium, silicon, aluminium and iron react to form the calcium silicates, aluminate and aluminoferrite which are the principle active compounds of portland cement. This process is completed at a temperature of around 1400°C, the resulting product is portland cement clinker.

6) The clinker is cooled to a temperature which is convenient for handling (60 - 150°C). The clinker may then be sent directly to the finish grinding mills, but usually it is stockpiled. Clinker may be stored for relatively long periods without deterioration and for this reason it is possible to supply cement to places at great distances from the works by shipping clinker rather than cement. The final grinding of the clinker to produce cement can then take place at grinding mills nearer its destination.

7) During the grinding process a small proportion of gypsum is added to control the setting time of the finished cement. Additives for masonry and other special cements are incorporated at the grinding stage.

8) The finished cement is stored in silos for a short time before being dispatched to the customer in bags or in bulk.

There are three main types of manufacturing process in use today, wet, dry and semi-dry. These are described in detail in Appendix 2.

3.8 The Rotary Cement Kiln.

The kiln is often regarded as the heart of the cement manufacturing plant. It is the most expensive item of plant both in terms of the initial capital cost and in terms of energy requirement.

The first cement kilns were constructed on a vertical axis. These were called 'shaft kilns' into which alternate layers of fuel and raw material were packed and the kiln was then set alight. Once the operation was under way and the kiln was alight, burnt clinker could be removed from the bottom while additional layers of fuel and raw materials were added into the top.

Rotary kilns were developed towards the end of the last century[38], and the first patent was issued to Frederick Ransome in 1885.

Rotary kilns have several advantages over shaft kilns, They require less manpower to operate and have a higher output rate, but perhaps their biggest advantage is that the end product is much more uniform. The disadvantage of rotary kilns is a high energy requirement.

The fuels used for firing rotary kilns include coal, oil and gas, (the use of pulverised domestic refuse as a part replacement for other fuels has also been used succesfully).

The kilns used in conjunction with the wet process are proportionately longer than those used with a dry process. The extra length is required as a drying zone to drive off any moisture remaining in the feed materials.

Once it has been thoroughly dried, the raw material is raised to the decarbonisation temperature of 800°C. As the temperature continues to rise the calcium carbonate disassociates into calcium oxide and carbon dioxide and the transformation of the oxides of calcium, silicon, aluminium and iron into the active ingredients of portland cement begins. This transformation, which results in the production of portland cement clinker, is completed in the hottest part of the kiln at temperatures of around 1400°C .

Kilns used with the dry process are basically similar to those described above except that they are shorter in length as no drying zone is required. In modern dry processes, before it enters the kiln the raw material is passed through a suspension preheater. The preheater consists of a series of cyclones in which the feed meal is exposed to the hot exhaust gases leaving the kiln.

A full four stage preheater raises the temperature of the meal to around 800°C so that even before it enters the kiln it is already 40% calcined. In smaller installations the preheater merely serves to thoroughly dry the meal before it enters the kiln.

After firing is completed, the clinker has to be cooled before it can be handled and several types of cooler are in general use.

After cooling, the clinker is transferred to storage.

3.9 Clinker Grinding.

The clinker produced after firing and cooling is much more stable than finished cement and can be stored under cover for several weeks without degrading.

Cement clinker is ground into the finished product in tube mills similar to those used to grind hard materials in the dry process.

Clinker is harder to grind than the raw materials and must be ground finer, the size of the mills and the grinding times are both therefore greater than used for the raw materials.

A typical tube grinding mill is a revolving cylinder which is divided into two or three compartments. These contain size-graded steel grinding media which, by a combination of impact and friction reduce the clinker to the required fineness.

At the grinding stage, gypsum is added to the clinker to control the setting time of the finished cement. The amount of gypsum which is added is generally around 3 - 5% by weight. Any other additives for the production of special or blended portland cements are also added at this stage.

After grinding the cement is then ready for distribution and use.

3.10 The Chemical Structure of Cement.

The term 'cement' can be used to cover a wide range of adhesives but it is used here only to describe those which have lime as a principle constituent. These should strictly be called 'calcarous cements'.

Nearly all the cements in use owe their cementitious properties to the formation of hydrated calcium silicates, aluminates or alumino sulphates, or to compounds of two or more of these groups.

The chemical formulae used to describe cement chemistry are often expressed as a sum of oxides, thus tricalcium silicate ($Ca_3.SiO_5$) can be written as $3Ca.SiO_2$. To further simplify matters, those oxides most commonly encountered are often abreviated eg. C for CaO and S for SiO_2.

The clinker of Ordinary Portland Cement (OPC) as it leaves the kiln contains four main phases : Tricalcium silicate (C_3S), β - dicalcium silicate (β-C_2S) Tricalcium aluminate (C_3A) and ferrite solid solution (approx. C_4AF). These four main compounds can be assumed to hydrate independantly of each other. Also present in many cement clinkers are smaller amounts of free lime (CaO), periclase (MgO) and alkali sulphates.

These phases are now considered in greater detail.

The main phase in most modern Portland Cements is a form of tricalcium silicate. This is often called 'alite'. C_3S decomposes into C_2S and CaO below 1275°C, but this reaction is usually sluggish and C_3S can occur metastably at room temperature.

Dicalcium Silicate C_2S can occur in four polymorphic modifications : α, α', β, and γ. Of these, α is non - hydraulic, α' gives poor strength and γ is almost inert. The usual form of C_2S found in portland cement is the β - modification, though small quantities of α'-C_2S have been found by microscopic investigation.

The ferrite phase in cement clinker is a solid solution which is usually taken to belong to the series C_2F - C_2A. The limit at the iron rich end is C_2F and at the aluminium end is approx C_6A_2F.

The fourth phase - Tricalcium Aluminate, C_3A has no polymorphic modifications.

Free lime, (calcium oxide, CaO) and periclase (MgO) are usually present in small quantities. The CaO derives from an incomplete reaction and the MgO is usually derived from the $MgCO_3$ of the original limestone.

3.11 Reactions in the Kiln.

The reactions in the kiln occur in stages and these are summarised in Fig. 3.11.

Studies have shown that the content of free CaO rises to a maximum at a point some distance before the burning zone. This suggests that at 900 - 1000 °C decomposition of $CaCO_3$ occurs more rapidly than reaction of the resulting CaO with the aluminosilicates.

Immediately before the burning zone, the free CaO content drops again and the temperature rises sharply to 1250°C. Both effects are probably caused by the exothermic reaction of the CaO with the aluminosilicates. As the mixture passes through the burning zone the reaction is completed and the free CaO content drops to almost zero.

At the 'clinkering' temperature of between 1300 and 1500°C the product consists essentially of crystals of C_3S and C_2S, formation of which is largely completed at this stage, together with a liquid containing CaO as well as most or all of the Al_2O_3, Fe_2O_3, and MgO, but relatively little SiO_2. The aluminate and ferrite phases therefore only form during cooling.

The exact sequence of reactions by which the cement compounds are formed is not well understood. There is general agreement however, that whatever the mechanism, equilibrium conditions are closely approximated to at the clinkering temperature, assuming that grinding, mixing and burning are properly carried out.

Temp. (°C)	Process.	Thermal Change
100	Evaporation of free water	Endothermic
500 +	Dehydroxylation of clay minerals	Endothermic
900 +	Crystallisation of products of clay minerals dehydroxylation. Decomposition of $CaCO_3$.	Exothermic
900-1200	Reaction between $CaCO_3$. or CaO and aluminosilicates.	Exothermic
1250-1280	Beginning of Liquid formation	Endothermic
1280 +	Further liquid formation and completion of formation of cement compounds.	

FIG. 3.11 Reactions in the Kiln.

The rate at which clinker is cooled can effect the properties of the resulting cement. Certain slowly cooled clinkers show 'flash set', slow cooling may also result in an unsound cement if the clinker contains a relatively high (2.5 - 5%) proportion of MgO.

Rapidly cooled clinkers may result in cements which are more resistant to sulphate attack. Rapidly cooled clinkers therefore appear to be more desirable with the exception that slowly cooled clinkers can be easier to grind.

The composition of a typical cement[39] containing gypsum is given in Table 3.1.

The four major compounds are C_3S, C_2S, C_3A and C_4AF. C_3S has all the essential properties of cement, it undergoes an initial and a final set within a few hours of gauging and when properly prepared shows no unsoundness. Mixes of tricalcium silicate and water are less plastic than cement and more water is required to obtain a workable paste.

Dicalcium Silicate, C_2S, has no definite setting time and the guaged mass sets only slowly over several days.

Tricalcium Aluminate, C_3A gives a 'flash' ie. almost instantaneous set on gauging with water and this is accompanied by the evolution of so much heat as to lead to steaming.

On further mixing so as to break up the flash set a plastic easily workable mass is obtained, but if placed in water this disintegrates and crumbles away.

C_4AF hydrates rapidly and developes a low strength. Setting occurs in minutes though it does not show a flash set like C_3A. Marked heat evolution also occurs, though less vigorously than with C_3A .

Compound.	%
C_3S	46.0
C_2S	23.1
C_3A	5.7
Ferrite	15.7
Gypsum	4.1
CaO	0.8
MgO	2.8
Unassigned T_iO_2) Alkalis, part of) ignition loss.)	2.0

TABLE 3.1 **Typical Cement Composition.**

3.12 Types of Cement.

There are several types of portland cement in production today. By far the most common is 'Ordinary Portland Cement', usually abreviated to OPC.

This is the standard cement of the Construction Industry and its composition is controlled by British Standard BS 12. It should be noted that the requirements of BS 12 are only limits and different manufacturers produce cements of very different composition within these bounds.

Rapid Hardening Portland Cement, (RHPC). is very similar to OPC, it differs in that it is more finely ground. This allows hydration to occur more rapidly and hence it gains strength earlier than OPC. The chemical composition of RHPC differs slightly from that of OPC, but it is also governed by BS 12.

The finer particle size of Rapid Hardening Portland Cement may be an advantage if used in a carbon fibre/cement composite as it could allow the cement paste to penetrate the carbon fibre tows more easily.

Sulphate Resisting Portland Cement (SRC), is used where there is a risk of the concrete being attacked by sulphates, either in the ground, or perhaps as the result of some chemical process. SRC derives its sulphate resistance from a low content of tricalcium aluminate, C_3A. The lowering of the C_3A content, which hydrates rapidly also lowers the heat of hydration and although SRC has a finer particle size than OPC its heat of hydration is lower. The composition of SRC is controlled by BS 4027.

Other types of cement are available, such as white portland cement and masonry cement, but these are produced in much smaller quantities and are not considered here.

3.13 Hydration of Cement.

Hydration is the term used to describe the chemical reaction which takes place between the various cement compounds and water.

The chemical reactions which occur result in the liberation of heat. If the rate at which heat is given off is recorded over a period of time it becomes obvious that it is not a constant process, but in fact, has at least three 'peaks'. This is illustrated in Fig. 3.12.

The first, and highest, peak is reached very rapidly and is followed by a period over which the rate of heat liberation drops very low. During this so called 'dormant' period the cement paste stiffens and its workability decreases. This puts a practical limit on the time available for placing wet concrete.

At the end of the 'dormant' period the rate of heat liberation increases again as setting begins. A third, lesser, peak is reached some time later, though the size of this peak and the time when it occurs varies with different types of cement.

It seems likely that the peaks in the rate of heat evolution during the hydration process are related to the hydration of the different compounds within the cement. The hydration process therefore may be studied by considering the hydration of these individual compounds.

The most important compound in cement paste is *Tricalcium Silicate* from which much of the strength of cement is gained. The hydration products of this phase are a calcium silicate hydrate and calcium hydroxide.

The hydration of *Dicalcium Silicate* takes place relatively slowly and consequently it contributes little to early strength, but it may add to late strength if the hydration process is allowed to continue.

Tricalcium Aluminate reacts very rapidly with water and the products of the hydration are formed as platelets. The speed of reaction of C_3A is such that a flash set will occur unless gypsum has been added as a set controller. The rate of heat liberation during this hydration makes a significant contribution to the second peak of Fig. 3.12. This peak is controlled by the presence of gypsum which reacts with the C_3A to form 'ettringite'. If the amount of tricalcium aluminate present is greater than can be controlled by the gypsum then the third peak is produced.

The hydration of the *Calcium Aluminoferrite* phase (C_4AF) in the presence of gypsum produces an iron-substituted ettringite.

The four main phases of cement paste can be considered to hydrate independently although some interactions do occur. The hydration of tricalcium silicate is accelerated by the presence of soluble sulphates and the lime which is produced influences the course and rate of hydration of the tricalcium aluminates and the calcium aluminoferrites.

It has been shown that the hydration of C_3S makes a significant contribution to the second peak in Fig. 3.12, as does the hydration of C_3A. The ferrite phase has a lower heat of hydration than the silicate phase and it contributes little to this second peak.

The hydration of all the phases contributes to the first peak, but the major contribution is from the tricalcium aluminate, especially if this is not sufficiently retarded by the presence of gypsum.

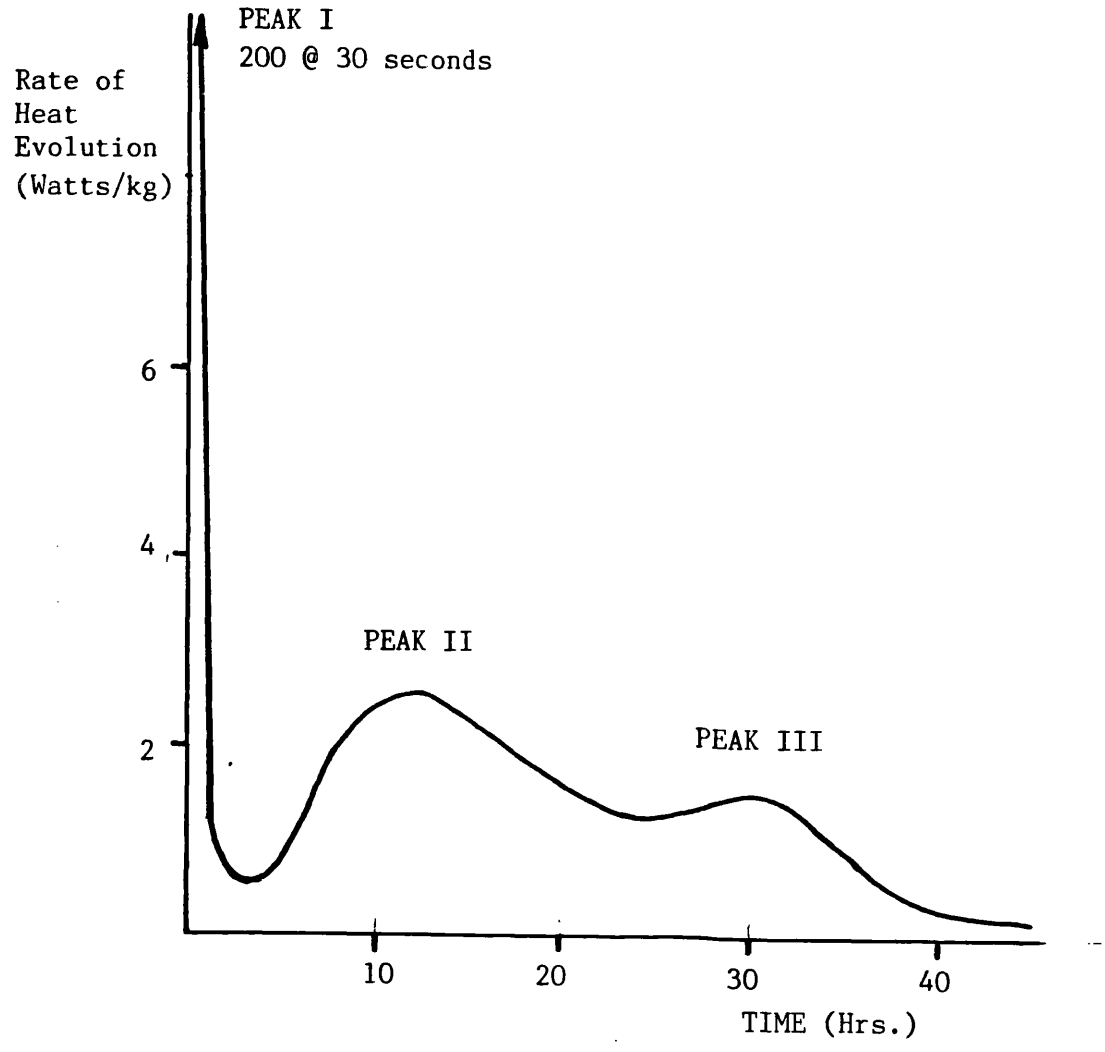


FIG. 3.12 **Heat Liberation during the Hydration of Ordinary Portland Cement.**

3.14 Physical Structure of Cement Paste.

The mechanical strength of the cement paste is derived from the interlocking of the crystals of the hydration products formed on adjacent grains of the cement minerals. As more crystals interlock the paste becomes stiffer and setting occurs.

The growing crystals of the hydration products take up the space originally occupied by the free water. If not enough water is available then incomplete hydration results. Alternatively, if the amount of water available is greater than that required for hydration then the uncombined water forms voids in the hardened paste resulting in reduced strength.

The space requirement for complete hydration of the cement minerals dictates a water/cement ratio of approximately 0.35. The workability of the paste has to be considered and a water/cement ratio as low as this would produce a very stiff paste.

For a practical cement paste the water/cement ratio has to be increased above the minimum required for greatest strength and the value finally chosen is a compromise between matrix strength and workability.

The water/cement ratio which is commonly accepted as the standard in the construction industry is 0.6. This relatively high value is partly dictated by the need for sufficient workability for the placing of concrete around reinforcement. A lower degree of workability may be acceptable if the requirement is for plain mass concrete.

CHAPTER FOUR

The Manufacture of a Carbon Fibre Reinforced Cement Composite

4.1 Introduction.

One of the major problems to be overcome in the manufacture of a carbon fibre/cement composite is the difficulty of fully investing a fibre tow with matrix material.

The particulate nature of cement, and the large size of the cement particles relative to the fibre diameter, make it difficult for the matrix to fully penetrate a dense fibre tow and bond with every fibre.

If a tow of carbon fibres is to be used efficiently every individual fibre must be in contact with the matrix.

As part of this current reserch a great deal of work was carried out to determine the best way of overcoming this potential problem. Two different approaches were tried and these were compared to decide which was the most effective.

The first, the **'Fibre Spreading'** approach sought to improve matrix penetration by increasing the inter-fibre separation. In the second, which was referred to as the **'Prepreg'** approach, the difficulty of peretrating a fibre tow with a particulate matrix was avoided by using an 'intermediate' resin matrix. This bonded the fibre tow internally so that the cement had only to bond with the surface of the tow in order to transfer load to the fibres through the intermediate matrix.

After establishing a method of preparing the fibres to receive the cement matrix, a method of producing cement plates reinforced with unidirectional fibres was developed.

The structural properties of the composite plates produced by this method were then determined by means of tensile tests.

In order to determine whether the composite was behaving as well as it should a theoretical model of the plate behaviour was developed. By analysis of this model and comparison with the experimental results it was possible to determine the efficiency of the composite, ie. whether it used the properties of the carbon fibres economically.

4.2 Fibre Preparation : Fibre Spreading Approach.

The 'fibre spreading' approach seeks to improve matrix penetration of the fibre tows by increasing the fibre separation.

In previous work,[22] fibre separation was increased by easing the tows apart by hand. However, it was found that this method did not produce an even distribution of fibres and resulted simply in smaller dense bundles. The method did have the advantage of being simple but also had the significant disadvantage of a high potential for fibre damage.

Because of its crudity and the risk of fibre damage the hand-spreading of fibres was not thought worthy of further consideration.

The use of water as a medium for spreading fibres had been used in other research[40]. This method appeared to have some potential and it was therefore further explored in this research in some detail.

A method of spreading fibre tows using a water flume was developed over several weeks of trials which involved comparisons of many different techniques.

The apparatus used in the water flume method is illustrated in Fig. 4.1. The carbon fibre tow was fed from the Spool 'A' and entered the Flume Channel. It then passed under the Sprinkler 'B' which introduced water across the full width of the flume bed.

As the tow passed down the flume, which was about 2.0 metres long, the fibres were separated by the action of the water and the tow spread to a width of approximately 150mm.

At the lower end of the Flume Channel the fibre veil was passed under a Drier 'C' and was wound onto a take-up spool where it was interleaved with backing paper.

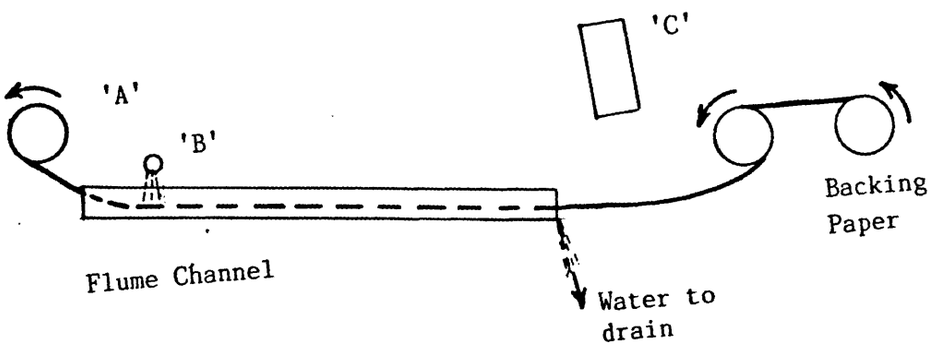


FIG. 4.1 The Water Flume.

In practice it was found that in a continuous process it was not possible to dry the fibre veil sufficiently quickly. As the spread veil left the water at the foot of the channel the surface tension of the water tended to pull the fibres together into dense strands and the even distribution which was present in the flume channel was lost.

The tension applied to the tow in the flume proved to be an important factor. If the tension was too high the fibres did not separate as effectively. Alternatively, if the tow was allowed to become slack it drifted down the flume with the water faster than it could be dried and taken up.

Overall, the results of this process were not very satisfactory. Because of the problems of drying the fibres the distribution which was achieved was uneven. The problems of controlling the tow tension resulted in only very short production runs being possible.

Many of the problems of the water flume spreading method were inherent in the use of water as the spreading medium. The water performed the function of spreading the fibres relatively well, but it proved difficult to dry and re-separate the fibres once the surface tension of the water had pulled them together into dense strands upon leaving the flume channel.

To overcome the problems of the water flume a 'dry' spreading method was devised. Like the wet process this method was developed over several weeks of trials which involved several stages of improvement.

The apparatus used for the dry spreading method is illustrated in Fig 4.2.

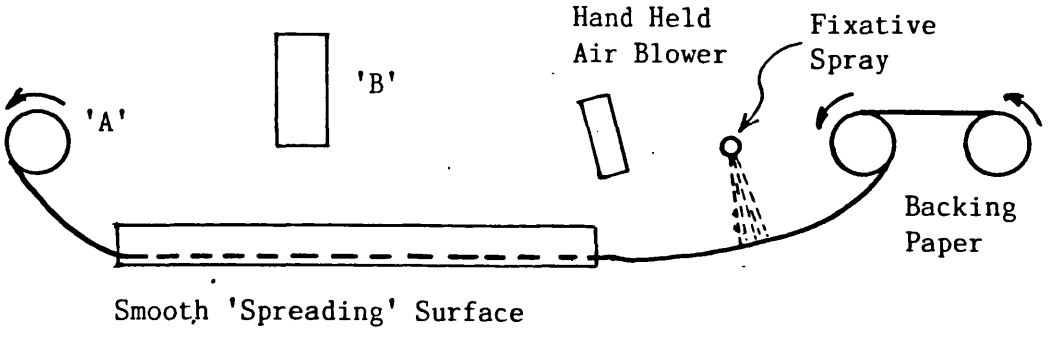


FIG. 4.2. The Dry Spreading Process.

In this process after leaving the Feed Spool 'A' the fibre tow travelled across a smooth surface, it then passed under a low power Fan Unit 'B' which played a gentle current of air onto the fibres and eased them apart.

After passing under the Fan Unit the fibre distribution in the veil was quite good. It could be further improved, and any dense bundles separated, by a hand held air blower which was played onto the spread fibres.

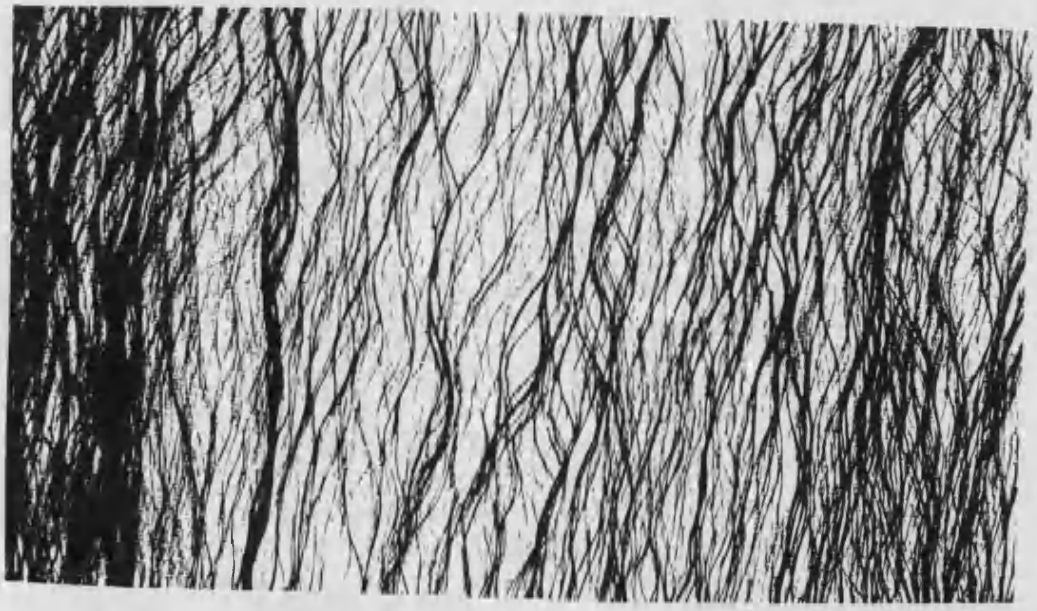
The fibre distribution in the veil was then 'fixed' by the application of a water soluble fixative spray and the veil was wound onto the take-up spool where it was interleaved with a backing paper.

This dry method was considerably faster than the water flume and produced a fibre veil with a much more even fibre distribution. However, it was found that if the tow tension was too high, this resulted in denser bundles of fibres at the outer edges of the veils.

A comparison of the fibre distributions achieved by the two methods is shown in Fig.4.3. It can be seen from this that the dry method produced a much broader veil of spread fibres and achieved a more even fibre distribution than the water flume.

The dry spreading method appeared to be a practical means of increasing the fibre separation to allow easier matrix penetration.

a) Water Flume Process.



b) Dry Spreading Process.

FIG. 4.3 Comparison of Fibre Distribution.

4.3 Fibre Preparation : The Prepreg Approach.

Fibres which have been preimpregnated with a resin matrix are commonly known as 'Prepreg'. This abreviation is adopted here.

Resins, because of their free flowing, non-particulate nature, are ideally suited to the impregnation of dense bundles of fibres and it is possible to achieve complete tow penetration with all but the most tightly packed arrays.

If a tow of carbon fibre is preimpregnated (prepregged) with a resin which bonds the fibres together then the need for the cement matrix to penetrate the tow is obviated.

The cement has only to bond with the surface of the prepregged tow and stress transfer to all fibres will then take place through the resin.

As resins do not require large fibre separation to be able to penetrate a tow there is no need for prespreading of the fibres.

Prepregs using different combinations of fibre and resin are widely available. They are used throughout the composites industry in the production of high performance composite materials.

Two factors are important when considering the choice of a resin system. Firstly, it must be suitable for bonding with both the fibres and the cement. Secondly, the cost of the resin must be considered. The material cost of carbon fibre is itself high and if it is to be commercially viable the additional costs of composite manufacture must be kept to a minimum.

The most commonly used matrix system in commercial prepregs is Epoxy Resin and therefore in this research the possible use of an Epoxy Resin matrix system was initially considered.

Epoxy resins have extremely good mechanical properties and their use in prepregs has enabled the production of composite laminates which combine the advantages of high strength and low weight.

The usual method of producing a composite laminate using epoxy prepreg involves stacking several sheets of prepreg on top of each other. Heat and pressure are then applied and the resin in each layer flows and forms a continuous matrix throughout the composite.

This method was obviously inappropriate to the use of epoxy prepregs in combination with cement where two dissimilar matrices were involved, one of which was not thermoplastic. This incompatability highlighted one of the potential problems of an epoxy prepreg/cement composite.

Composite performance relies on a good bond between fibre and matrix to transfer stress across the interface. The bond may be a chemical adhesive bond, or it may rely on frictional shear stress to transfer load. In either case, if the bond breaks down the fibres will be unable to carry any further load and the composite will fail according to the strength of the matrix.

In the case of epoxy resin and cement there will be no chemical bond and therefore stress will be transferred across the resin/cement interface by friction. The frictional resistance of this bond is likely to be low. When the cement paste comes into contact with the epoxy resin it will mirror the surface qualities of the resin. The surface of the resin is smooth with few irregularities and therefore the coefficient of friction will be small.

The potential cost of such a composite has also to be considered, carbon fibre/epoxy prepreg is extremely expensive (£800 for $20m^2$ @ 1983 prices.) Even allowing for possible cost reductions on large orders a material cost as high as this precludes the use of epoxy prepregs from ever being a commercially viable method of reinforcing cement.

This combination of high material cost and doubts about the structural viability of the epoxy/cement bond resulted in the consideration of alternative resin systems.

One such alternative is Polyvinyl Acetate (PVA). This is a polyvinyl ester adhesive which is used in the form of an aqueous dispersion[41]. PVA emulsion glue is a versatile industrial adhesive which is widely used for porous or fibrous materials such as paper, wood or leather.

Another recognised application is the use of PVA emulsion as a bonding agent to increase the adhesion between new and old concrete. This can be done in one of two ways, either by coating the old concrete with PVA before the new concrete is applied, or by including a proportion of PVA in the new mix.

The manufacture and nature of PVA are described more fully in Appendix 3.

It seemed that PVA would be viable as an alternative to epoxy for use as the resin matrix in a carbon fibre prepreg. It had potential advantages which included water solubility and a proven ability to bond with cement paste.

A commercial source for carbon fibre/PVA prepreg could not be found and it was therefore necessary to develop a method of preimpregnating carbon fibre tows with PVA resin in the laboratory.

Initially a method based on the filament winding technique, commonly used in the composites industry, was employed to produce flat sheets of carbon fibre/PVA prepreg containing many parallel tows.

4.4 Prepreg Filament Winding.

The filament winding process which was developed is illustrated in Fig. 4.4.

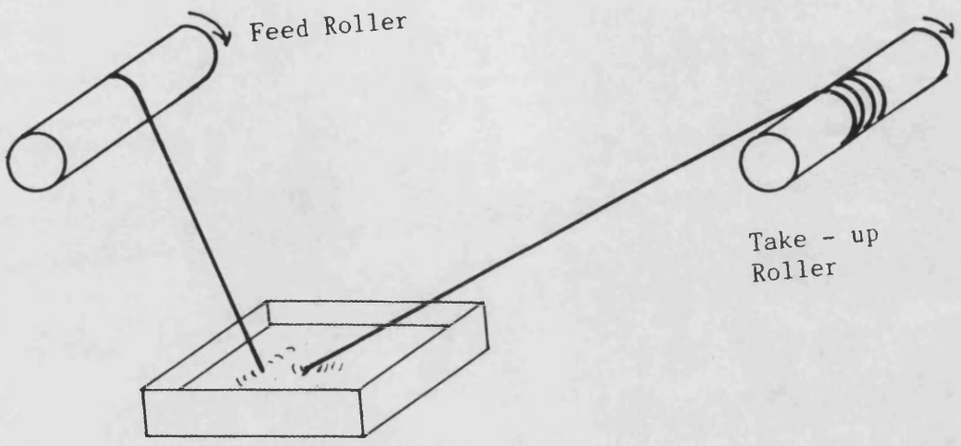
The tow of carbon fibre was fed from the spool 'A' and passed through a bath containing PVA emulsion. A guide mechanism incorporated into the resin bath kept the fibres submerged.

In early trials, a small fan unit was used to ease the fibres apart before they entered the bath. It was thought that this would improve matrix penetration of the tow, but this was later discarded as unnecessary.

After the fibres left the resin bath, the impregnated tow was wound helically onto the take-up roller. This roller had a smooth plastic surface and was approximately 100mm in diameter.

The impregnated tow was guided onto the take-up roller by hand to avoid overlapping tows and void areas. As the tow passed through the fingers surplus resin was removed by slight pressure.

The winding process continued until 100 revolutions of the take-up roller had been made. This produced a sheet width of approximately 400mm.



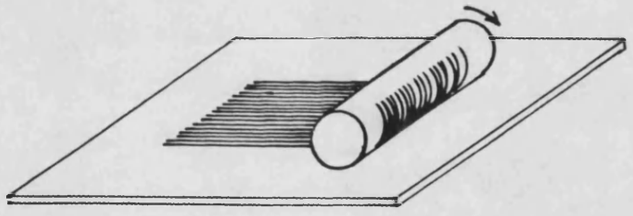


FIG. 4.4 Filament Winding Apparatus.

A cut was then made, normal to the fibre direction with a sharp bladed knife. The roller was lifted off its bearings and the still wet prepreg was rolled off the roller onto a flat perspex sheet.

When it was dry the prepreg sheet could be simply peeled off the perspex. At this stage it was important to take care to avoid creasing the prepreg as this could have damaged the fibres.

Flat sheets of carbon fibre/PVA prepreg measuring approximately 300mm long x 450mm wide were successfully produced by this method. Each sheet contained 100 aligned tows of carbon fibre.

4.5 Evaluation of Fibre Preparation Techniques.

Two possible methods of overcoming the problem of fully penetrating a tow of carbon fibres with a cement matrix have been described. At this stage in the research it was decided to evaluate the two techniques to determine which would be the most successful.

To compare the two methods, samples of carbon fibre reinforced cement (CFRC) were prepared using fibres which had been prepared using the 'dry spreading' and 'prepreg' techniques. These samples were then tested so that the properties of each composite could be determined.

By assessing the composite properties and by taking into account other factors, such as ease of manufacture, the most appropriate fibre preparation format was selected for further development.

4.6 Materials.

The type of carbon fibre used for both preparation techniques was 'Grafil XA-S' manufactured by Courtaulds UK Ltd. This is a high strength fibre (Specified tensile strength = 2900 N/mm^2) and is supplied unsized in a continuous 12K tow wound helically on a spool. The abreviation '12K' indicates that the tow contains twelve thousand individual filaments.

The PVA resin used for the prepreg technique was 'Tretol Timbabond 624' which is manufactured as a woodworking adhesive by Tretobond Ltd.

Before use the resin was diluted with water in the ratio 1-1. This dilution was necessary as the neat emulsion was too viscous to allow easy prepregging.

The cement paste was made up using Ordinary Portland Cement (OPC). This was selected as a standard for all samples. It is acknowledged that for the 'spread fibre' format a finer grained cement such as Rapid Hardening Portland Cement (RHPC) may offer advantages in easier tow penetration.

4.7 Composite Sheet Manufacture.

a) Using Spread-Fibre.

A veil of carbon fibres, approx 150mm wide was produced by the dry-spreading technique described earlier. It was decided to limit the width of the veil to 150mm as this was both more suited to the proposed test sample format and was easier to produce with an even fibre distribution than the greater widths which were possible.

The veil was cut into lengths of 350mm using sharp scissors. It was noted that the fibre distribution within the veil was not entirely even, being noticably more dense towards the edges.

A cement paste having a water cement ratio of 0.4 was made up. This water cement ratio was chosen as a reasonable compromise between that required for optimum matrix strength (0.3 - 0.35) and that required for good workability. (0.5). The consistency of the paste seemed reasonably well suited to the purpose.

The composite sheets were formed in plywood moulds which measured 300 x 150 x 6mm dp. The moulds had been treated with mould oil.

A layer of the cement paste was 'painted' onto the bottom of the mould using a brush. A tow of the spread fibre was then placed on this and another layer of the cement paste was then applied.

The process was repeated until 30 tows of carbon fibre had been used. The top surface of the sample was then smoothed off.

The composite sheets were cured under wet sacking for seven days.

After demoulding, each cement sheet was sawn into three strips, each 50mm wide, to give the desired test sample size of 300 x 50 x 6mm.

Manufacture of composite sheets using the veils of spread fibre proved to be fairly straightforward. The short lengths of veil were easy to handle, though longer lengths may cause problems. Application of the cement paste by brush was simple but it is possible that this rather crude method may involve some fibre damage.

b) Using Carbon fibre/PVA Prepreg.

Sheets of Carbon Fibre/PVA prepreg were produced using the filament winding technique described earlier.

The prepared prepreg was cut into strips 45mm wide parallel to the fibre direction. Care was taken to ensure that the cuts were made exactly parallel with the fibres and did not cut across them. This was quite difficult to achieve as the fibre tows were not clearly defined and it was not easy to discern the exact fibre orientation.

The cement paste was made up using a water/cement ratio of 0.35. This ratio was chosen for optimum matrix strength and the reduced workability was considered acceptable as the matrix did not have to penetrate the tows.

A layer of cement paste was brushed onto the bottom of a plywood mould which measured 300 x 50 x 6mm. A strip of the prepreg was then pressed down onto this and another layer of cement paste was applied

The operation was repeated until five strips of prepreg had been included. The top surface of the samples were trowelled smooth and the sheets were cured under the same conditions as the 'spread-fibre' samples.

The fabrication of the samples by this method was extremely straightforward. It was noted that because only five sheets of prepreg were used in each sample the layers of cement between the prepreg strips were quite thick. The prepreg itself was easy to handle and seemed less prone to damage either during handling or during plate fabrication than the spread fibre veils.

4.8 Determination of the Fibre Content.

According to the 'Rule of Mixtures' the ultimate strength of a composite sheet is directly proportional to the fibre volume fraction.

The fibre volume fraction of the various materials was calculated as follows :

a)Area of 12K Tow of Carbon Fibre (Grafil XA-S).

From Grafil Data Sheets:

Mass/metre = 800 mg
Density = 1.81 g/cm^3

Therefore, fibre volume in a 1.0 metre length is given by :

$$v = 0.80/1.81 = 0.4419 \text{ cm}^3$$

Hence, the cross-sectional area of a 1.0 metre length is :

$$A_f = 0.4419/100 = 0.4419 \times 10^{-2} \text{cm}^2$$

$$\therefore A_f = 0.4419 \text{ mm}^2.$$

b) Fibre Volume Fraction : Spread-Fibre Composite Sheets.

The Fibre volume fraction V_f was calculated for the full width (150mm) sheets. This was determined by dividing the known fibre area by the measured sheet dimensions.

eg. Carbon fibre area (30 Tows) :

$$A_f = 30 \times 0.4419 = 13.26 \text{ mm}^2.$$

Area of composite sheet :

$$A_1 = 150 \times 6 = 900 \text{ mm}^2.$$

Therefore the fibre volume fraction of the sheet is given by :

$$V_f = 13.26/900 = 0.0147 \text{ (say)}.$$

c) Fibre Volume Fraction : Carbon Fibre/PVA Prepreg.

This was calculated for the full sheet of prepreg :

Fibre area (100 Tows) :

$A_f = 44.19 \text{ mm}^2$

Area of Prepreg Sheet :

$A_p = 450 \times 0.28 = 126 \text{ mm}^2$

Therefore, the fibre volume fraction of the prepreg is given by :

$V_{fp} = 44.19/126 = 0.35$ (say).

d) Fibre Volume Fraction : Prepreg Composite Sheet.

Number of prepreg sheets = 5
Mean width of sheets = 45mm (say)

Total width of prepreg = 5 x 45 = 225 mm

Mean sheet thickness = 0.28 mm

Therefore, area of prepreg is given by :

$A_p = 225 \times 0.28 = 63 \text{ mm}^2$.

Hence fibre area of prepreg is given by :

$$A_f = 0.35 \times 63 = 22.05 \text{ mm}^2$$

Area of composite sheet = 50 x 6 = 300 mm^2. (say)

Therefore, the fibre volume fraction of the composite sheet is :

$$V_f = 22.05/300 = 0.735.$$

The figures given in the examples above are based on typical sample dimensions to explain the method. The fibre volume fractions derived are therefore only approximate. True values for V_f in each case were calculated from recorded sample dimensions and these are given in the results later.

4.9 Test Programme.

The composite sheet samples were tested to failure in tension using an 'Instron 1195' test machine.

To protect the surface of the samples from being damaged in the jaws of the test rig, aluminium end plates, measuring 100 x 50mm, were glued onto the faces of the samples at each end.

It is notoriously difficult to carry out tensile tests on cement samples and care is needed both in preparation and execution.

If the sample is not perfectly aligned along the axis of the test rig secondary stresses can be introduced. These secondary stresses are difficult to quantify and may lead to premature failure of the the sample before its true tensile strength is reached.

Stress concentrations can be generated around the jaws of the test rig and around any surface irregularities of the sample itself. These could also result in premature failure.

Because of these problems it is very difficult to obtain an accurate measurement of the tensile strength of such a composite sheet from tensile tests.

As sample failure will undoubtedly be due to a combination of direct tensile and other secondary stresses the results of such tests will be a lower bound for the true tensile strength.

4.10 Summary of Results.

The full results of the tensile tests are given in Appendix 4. Table 4.1 gives a summary of the mean test results obtained.

4.11 Discussion of Results.

From Table 4.1 it can be seen that the mean ultimate tensile strength of the composite sheets reinforced with the spread-fibre was 18.95 N/mm^2 and the mean ultimate tensile strength of the prepreg reinforced sheets was 106.88 N/mm^2.

Fibre Format	V_f	Sample Area(mm^2)	Failure Load(N)	Failure Stress(N/mm^2)
Dry-Spread	0.0136	294.4	5580	18.95
Prepreg.	0.0920	298.4	31691	105.60

TABLE 4.1. Mean Tensile Test Results.

To compare these results it is necessary to consider the different fibre volume fractions of the two composites.

From the Rule of Mixtures, the theoretical composite strength in each case is given by $\sigma_f V_f$. If this is applied to the two formats considered in this comparison the following values are obtained.

Spread Fibre : 2900 x 0.0136 = 39.44 N/mm^2.

Prepreg : 2900 x 0.0920 = 266.8 N/mm^2.

By comparison of the ratio of actual composite strength in each case to the theoretical strength derived above an 'efficiency factor', 'Q' can be obtained, where :

$$Q = 18.95/39.44 = 0.48 \qquad \text{(spread-fibre)}$$

$$Q = 105.6/266.8 = 0.40 \qquad \text{(prepreg)}$$

It can be seen that although the prepreg reinforced samples gave higher strengths at failure the sheets reinforced with spread fibre were apparently performing more efficiently than those reinforced with the prepreg.

If efficiency were the only criteria, then the dry-spread fibre format appeared to offer the greater advantage. However, before selecting which method of fibre preparation had the most potential other factors were taken into consideration.

The fibre volume fraction of the spread-fibre sheets was very low at approximately 0.014 (1.4%). It will be recalled from the discussion in Chapter Two that the maximum fibre volume fraction is governed by the relative sizes of the fibres and cement particles and is given by the equations :

$$V_{fmax} = 2\pi/\sqrt{3}\,[r/(2r + D)]^2 \qquad \text{(Hexagonal)}$$

$$V_{fmax} = \pi\,[r/(2r + D)]^2 \qquad \text{(Square)}$$

Where $r = 6.8\ \mu m$ [42].

$D(mean) = 30\ \mu m$ [43].

Substituting these values for the fibre and particle sizes, it can be derived that the maximum volume fraction attainable with these components is in the range 0.076 - 0.088 (7.6 - 8.8 %) for square and hexagonal arrays respectively.

It will be recalled that the fibre volume fraction achieved with the prepreg reinforced composite was 0.092 (9.2%) which is in excess of the theoretical maximum attainable using spread fibre.

It is therefore theoretically impossibe to create a composite sheet using spread fibres with values of strength and modulus comparable with those achieved using the prepreg format. Even if the theoretical maximum fibre volume fraction could be exceeded (due to variations in cement particle size) it would require a very large number of tows (approx. 200) to achieve the same properties.

The higher fibre volume fraction of the prepreg reinforced composite is possible because the fibre separation required in the prepreg format is much lower than that required for penetration of the tows with a cement matrix. The properties of composites reinforced with the carbon fibre/PVA prepreg can therefore be proportionately higher.

This was demonstrated by the results of the tests carried out for this comparison where much greater composite strengths were obtained with the prepreg reinforced samples.

Another factor to be considered was that the sample fabrication process was much faster and simpler with the prepreg sheets than with the spread-fibres. This was due to the high number of layers of reinforcement required with the spread-fibre format. (ie. 30 compared to 5 with the prepreg)

It was also noted that the prepregged fibres, being bound together by resin, seemed much less susceptible to damage and were also much easier to handle than the rather delicate spread-fibre veils.

4.12 Assessment.

After taking into account all of the relevant factors discussed above it was decided that the prepreg fibre format offered the most potential for use in a structural carbon fibre/cement composite sheet.

The major disadvantage of the spread-fibre format is the limit which it places upon fibre volume fraction and hence the ultimate composite properties. It is thought that this limitation could reduce its potential suitability for a use in a structural application.

The prepreg format apparently makes less efficient use of the properties of the carbon fibres and would therefore be relatively more expensive. This disadvantage is offset by the higher ultimate properties which are more easily attainable and which make the structural use of the composite a more viable proposition.

The results of this comparison showed that it was possible to produce a carbon fibre/cement composite material which had useful structural properties.

CHAPTER FIVE

Development of the Prepreg Approach

5.1 Introduction.

The results of the comparison between the spread fibre and prepreg approaches showed that Carbon fibre/PVA prepreg had significant potential for the reinforcement of a cement composite sheet. The format in which the prepreg would be used is now considered.

The densly packed, flat sheets of carbon fibre/PVA prepreg produced by the filament winding technique proved quite successful as reinforcement, but this prepreg format did have some disadvantages.

Manufacture of the prepreg by this technique placed a restriction upon the maximum size of sheet which could be produced. This was because the prepreg sheet was formed around a roller or 'mandrel' and the size of sheet was therefore governed by the diameter of the mandrel. For example, a six metre length of prepreg sheet would require a winding mandrel of 1.9 metres diameter. Longer lengths would require proportionately larger mandrels.

In order to produce a flat sheet, the prepreg had to be removed from the mandrel while still wet and flexible. If it was allowed to dry and harden before removal this operation became impossible. Significant difficulties are forseen in the handling of large sheets of wet prepreg although this operation proved quite easy on a small scale.

Apart from the practical difficulties of producing prepreg in this form on a large scale, there are potential problems with the use of such sheets as reinforcement.

The carbon fibre/cement composites produced using sheet prepreg consisted of a multi layered 'sandwich' of cement paste and prepreg.

This concentration of the fibres into densly packed layers attracts high interlamina shear stresses between the layers of prepreg and the cement. These high stresses could lead to premature failure of the composite before its full tensile strength is reached.

To overcome these problems an alternative prepreg format was considered. This consisted of individual tows of carbon fibre which were prepregged with PVA and were presented im the form of flat ribbons or tapes. The prepreg tape could, in theory, be of any length, but for ease of handling it was limited in this research to a maximum length of 2.5 metres.

It was thought that the use of individual tows rather than dense sheets would allow a more uniform distribution of reinforcement throughout the composite and the interlamina shear stresses between prepreg and cement would consequently be reduced.

A further advantage of prepregging individual tows was that because the fibres were not constrained by adjacent tows they were able to spread out further laterally. This resulted in thin, wide tapes with a larger surface area/volume ratio. This increase in the surface area of the prepreg gave a larger area for bonding to take place between the prepreg and the cement matrix.

5.2 Production of 'Single-Tow' Prepreg.

The prepregging of single tows of carbon fibre was carried out using the apparatus illustrated in Fig 5.1. The apparatus used was fairly simple, and the method had some similarities to that used previously for the production of prepreg sheets.

The carbon fibre tow left the feed spool 'A' and was submerged in a bath of PVA resin 'B'. After leaving the bath the tow was passed through a set of plastic coated rollers. These pressed the tow flat against a polythene backing strip which was fed in from underneath.

The prepreg emerged from the rollers as a flat tape about 15mm wide, which was held in position and protected during subsequent handling by the polythene backing.

The backing strip was introduced into the process after it was found that the prepreg tape had a tendancy to revert to a round tow unless it was pressed against something which held it flat. After trials of other materials, including perspex sheet, polythene was selected as it is soft and flexible and it was felt that this was least likley to cause fibre damage.

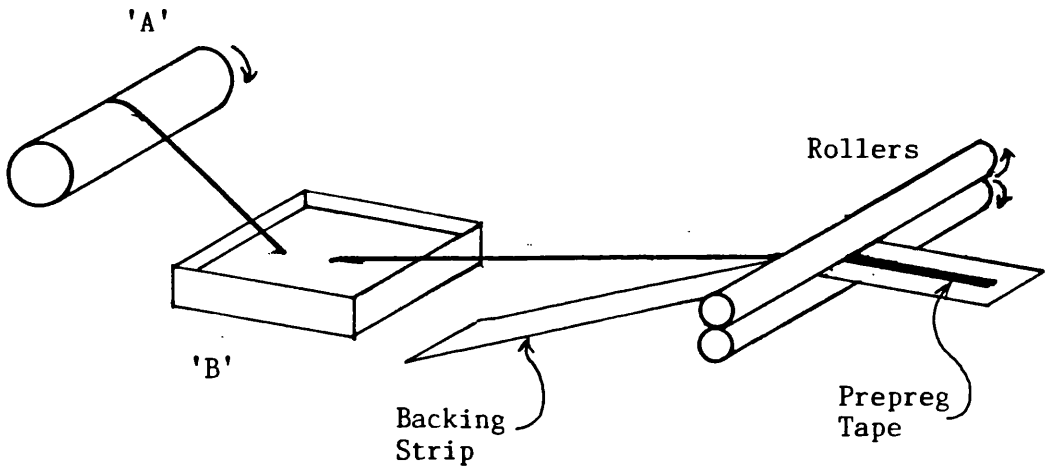


FIG 5.1 The Preimpregnation of Single Tows.

The pressure applied by the rollers was limited to that due to the self weight of the upper roller. It was found that if the pressure was increased above this then increased fibre damage resulted.

The prepreg tapes were then allowed to dry. Once dry the polythene backing strip could be easily peeled off. As the tapes were quite thin care was necessary when removing the backing to avoid the introduction of creases into the prepreg.

In order to determine whether this 'single-tow' prepreg was more efficient as reinforcement than the sheet format used previously a series of tensile tests was carried out on samples of carbon fibre/cement composite reinforced with prepreg produced by the single-tow method.

These tests are described in detail in Appendix 5.

It was found that carbon fibre/cement composite sheets reinforced with single-tow prepreg with a fibre volume fraction of 0.05 (5.0%) had an ultimate composite strength of 67.0 N/mm^2

The composite strength obtained from the test results was compared with that predicted by the 'Rule of Mixtures' and a strength efficiency factor of Q = 0.46 was obtained.

It will be recalled that the tensile tests on composite samples reinforced with 'filament wound' prepreg gave a strength efficiency factor of 0.4. It would appear from this that the use of individual tows of prepreg produced greater composite tensile strength efficiency than the flat sheet format.

Because of the increase in strength efficiency obtained by the use of individual tows it was decided that all further research would concentrate on the use of carbon fibre/PVA prepreg in the single-tow format.

5.3 Prepreg Properties.

According to the Rule of Mixtures the properties of a preimpregnated carbon fibre tow will be proportional to the properties of the fibre and the resin and to the volume fractions of the components. If it is assumed that the resin matrix does not contribute to the tensile strength, the most important factor will be the properties of the carbon fibre.

The ultimate strength of a tow of carbon fibre is determined initially by the degree of graphitisation during the manufacturing process, but this is then reduced by subsequent treatment.

The ultimate strength of such a tow will be reduced during the preimpregnation process by any fibre damage which may occur. It has also been shown that tow strength is related to the length of the fibres.

As part of the research these factors were considered and in addition, the relationship between resin dilution and the fibre volume fraction of the prepreg was examined.

5.4 Fibre Damage.

The structural properties of a sample of carbon fibre/PVA prepreg produced by the 'single tow' method described earlier will not be as great as the properties of the carbon fibre tow itself before preimpregnation.

If it is assumed that the prepreg follows the Rule of Mixtures and that the fibre failure strain is much greater than the matrix failure strain, (ie. $\epsilon_{fult} >> \epsilon_{mult}$). Then the contribution of the matrix can be ignored and the ultimate strength of the prepreg is given by the equation:

$$\sigma_1 = \sigma_{fu} V_f$$

If fibres are damaged or broken, either by the prepregging process or by careless handling at any stage, the damaged fibres will not be able to carry their full share of the applied load and the properties of the prepreg will be reduced.

Carbon fibres are extremely delicate and are very susceptible to damage. Several opportunities for damage occur between the time when the fibre leaves the production line and the time when it is eventually used in a composite.

Although there is the possibility of some damage occuring during handling and transport prior to the fibres being received in the laboratory, it is thought that by far the greatest opportunity for damage was during the prepregging process.

The process used for the production of 'single tow' prepreg was examined and this revealed several locations where fibre damage may have occurred. These are indicated in Fig 5.2 and are summarized here :

1) As the tow leaves the feed roller, possible abrasion against adjacent tows. Uneven tension in the tow could cause jerking.

2) & 4) As the tow enters/leaves the resin bath - possible abrasion against the edges of the bath.

3) During impregnation - Contact with the guide used to keep the tow submerged.

5) In the rollers - Contact with rollers, abrasion against rollers and adjacent fibres, excessive applied pressure may fracture fibres.

6) Removal of backing strip - Careless handling could cause creasing or other fibre damage.

These 'damage opportunities' were studied carefully and various means of reducing fibre damage were introduced.

The bearings of the feed roller were made as smooth as possible to reduce jerking of the tow as it left the spool.

In the apparatus used in this research the tow of carbon fibres was pulled from the spool under tension. This was considered to be rather unsatisfactory.

The process could be improved if the feed roller were rotated under power so that the fibre tow is then fed off the spool rather than being pulled. This would eliminate any sudden pull on the fibres at this point and would reduce abrasion against adjacent fibres.

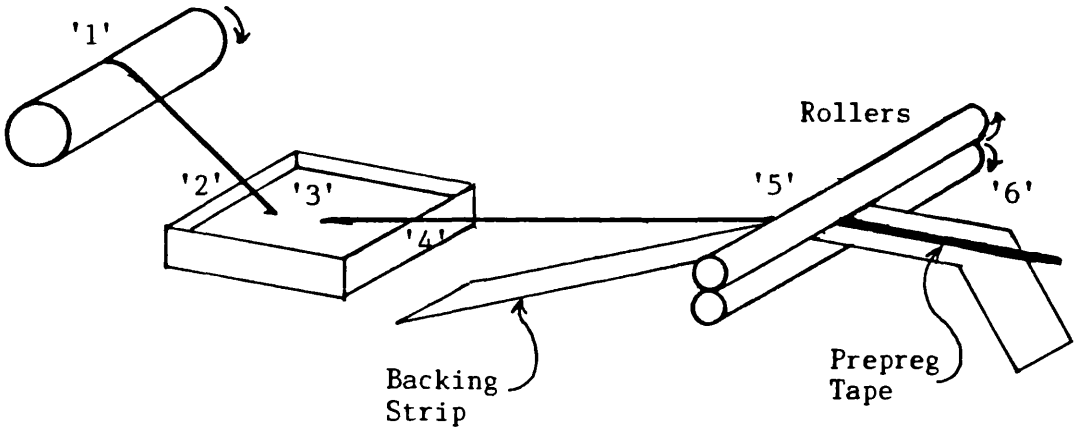


FIG. 5.2 Opportunities for Fibre Damage During the Preimpregnation Process.

All points of contact with the edges of the resin bath were kept as smooth as possible, sharp edges were avoided. One possible positive feature of the process is that as the tow leaves the bath the PVA resin may act as a lubricant to reduce friction.

The design of the guide which held the fibres submerged in the resin was considered in some detail as at the point where it passes through this guide the tow changes direction and it was thought that this was consequently one of the most important points of contact.

Initially, in early trials a simple wire loop had been used. Tests carried out on various alternatives revealed that a much better arrangement was possible. This consisted of a semi-circular arch which was fixed to the bottom of the bath.

The arch was formed from a varnished wooden ring of overall diameter approximately 50mm. The cross section of the ring was circular and approximately 10mm in diameter. The larger section diameter of this ring produced a much smoother curve under which the carbon fibre tow was passed.

As discussed in the previous section, it was found that if the pressure of the rollers was increased fibre damage became much more apparent. It was found that fibres were broken as they passed through the rollers and that the broken fibres would then stick to the rollers, pulling out of the tow and damaging other fibres in the process. Consequently roller pressure was kept to the minimum possible and this appeared to greatly reduce fibre damage.

No matter how much care was taken during the prepregging process it was inevitable that some fibre damage would occur.

The over-riding principle which must be considered when any work involving carbon fibres is carried out is that ***any*** contact with the fibres will result in fibre damage and therefore handling at any stage should be kept to a minimum. Where contact is unavoidable, care should be taken to ensure that the contact surfaces are as smooth as possible.

5.5 Fibre Length.

The tensile strength of any fibre is limited by the presence of imperfections. Such imperfections can be randomly distributed and of variable severity.

As the length of fibre which is to be tested is increased the pobability that a large flaw will be present in that length also increases, long fibres are therefore usually weaker than short ones.

If a single fibre is cut into sections of equal length, each section will have a different strength due to the random distribution of serious imperfections. The influence of imperfections upon the strength of composites has to be analysed with the aid of statistics.

If a number of fibres are gathered together to form a bundle or tow, the strength of the tow will be much less variable than that of the individual fibres. The average strength of the bundle will, however, be less than that for the individual fibres. For example, for fibres having a coefficient of variation of 50% for tensile strength, the bundle strength is only half of the mean fibre strength.

In a composite the situation is different, and the composite strength is higher than one would expect from the strength of individual fibres. If a fibre in a composite fails then stress can be redistributed by the matrix into adjacent fibres and back again.

Close to the fracture, adjacent fibres will take the higher stress for a short distance before it can be transferred back into the original fibre beyond the fracture.

The distance over which the higher stress is carried is so short it is statistically unlikely that a serious flaw will be present and so the adjacent fibres can carry the extra load without failing.

5.6 Experimental determination of the relationship between fibre length and strength.

Tensile tests were carried out on samples of carbon fibre/PVA prepreg to compare the strengths of two different sample lengths. Gauge lengths of 50 and 200mm were used. These tests are described in detail in Appendix 6.

From these tests it was found that the mean tensile strength of the longer samples was only some 75% of that of the shorter samples.

This reduction in strength will be partly due to the lower strength of the longer fibres, and partly due to the presence of imperfections in the prepreg.

These faults in the prepreg, typically kinks and twists, are introduced randomly by the prepregging process. The strength of the prepreg will therefore also depend upon the length tested. The greater the length of the prepreg sample, the greater the probability of a serious imperfection being present.

5.7 Resin Dilution.

The PVA resin used in the preimpregnation process was diluted with water. This was necessary as the undiluted PVA resin was considered to be too viscous to permit satisfactory preimpregnation. It could be expected that the resin volume fraction of the resulting prepreg would be to some extent related to the degree of dilution of the PVA.

To determine whether this was indeed the case, batches of prepreg were prepared using different degrees of resin dilution.

Samples of the prepreg from each batch were carefully measured and their cross sectional areas calculated. As the fibre area in each batch remained constant any variation in sample area must be due to a variation in resin content.

It was found that as the water content of the resin increased the resin volume fraction 'V_R' of the resulting prepreg decreased. This is illustrated in Table 5.1.

Another effect of increasing the water content of the resin was that the prepreg tows which resulted were considerably narrower and thicker than when lower water contents were used.

It was noted that the prepregs with more dilute resin appeared to be more susceptible to damage as they passed through the rollers.

RESIN/WATER	V_R
1 : 1	0.75
1 : 2	0.65

TABLE 5.1 Relationship between Resin Dilution and Resin Volume Fraction of Carbon Fibre/PVA Prepreg.

5.8 Determination of Prepreg Properties.

The structural properties of the carbon fibre/PVA prepreg produced by the single tow method were determined from the results of tensile tests.

As the results of such tests would have been influenced by variations in test proceedures a standard sample format and test method were adopted. These were then used for all tests.

5.9 Sample Format.

The preparation of samples of PVA prepreg for the tensile tests was carried out as follows :

Two metre lengths of carbon fibre were preimpregnated using the 'single tow' method described earlier. When these were dry, the backing strips were removed, and upto a maximum of two 150mm lengths were cut from the centre region of each tow using scissors.

The short lengths were then inspected, and any which had obvious defects such as kinks etc. were discarded.

Cardboard end tabs were affixed to the ends of the samples using an epoxy resin adhesive to give a standard gauge length of 50mm. In order to ensure that the end tabs were well secured, pressure was applied until the epoxy resin had set.

The standard sample format is illustrated in Fig. 5.3.

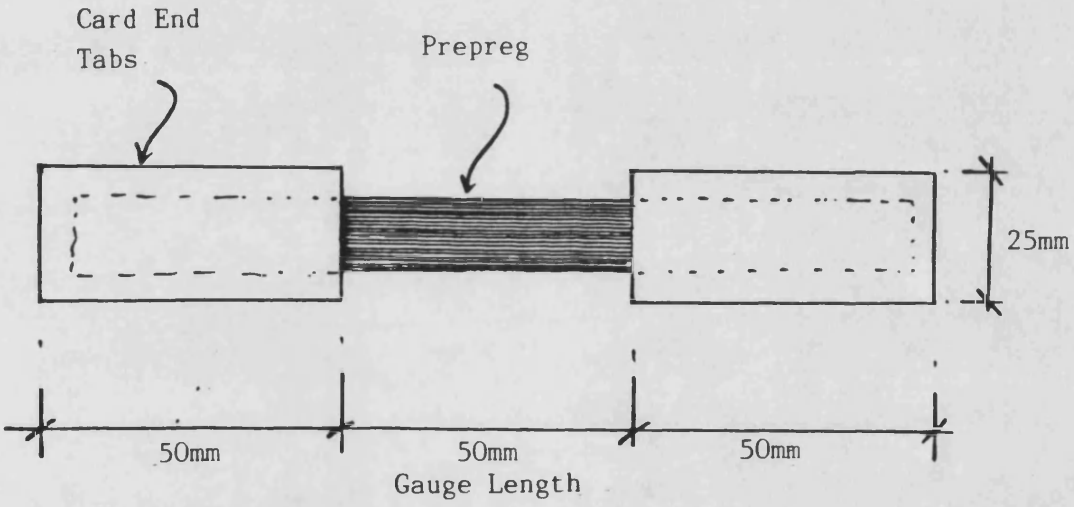


FIG. 5.3 Standard Prepreg Sample Format.

5.10 Test Format.

An 'Instron 1122' test machine was used to carry out all the tensile tests on samples of Carbon fibre/PVA prepreg.

The samples were held in the machine by means of two sets of grips. The lower set of grips were fixed in position and direction, the upper grips were connected by means of a universal joint which allowed movement in two horizontal dimensions.

The grip plates of the test machine measured 50 x 25mm and these exactly matched the end tabs of the samples. The samples were first positioned and gripped in the upper set and were then located and tightened into the lower set.

The rate of load application was controlled by the speed of cross-head displacement and a graph of load vs. cross-head displacement was automatically plotted by the machine. A standard cross-head speed of 0.5 mm/min was selected for all samples.

By ensuring that the grips of the test rig coincided exactly with the sample end tabs the guage length of 50mm could then be used as the basis for strain calculations.

5.11 Prepreg Behaviour Under Test.

The behaviour of all samples under test was very similar, and a typical plot of load against cross-head displacement is shown in Fig 5.4.

From this graph it was possible to determine the maximum load sustained by the sample and hence its tensile strength. Consideration of the slope of the graph allowed the elastic modulus to be calculated.

The portion of the graph 'O - A' represented the behaviour of the prepreg prior to failure of the matrix. The material was following the Rule of Mixtures and the composite modulus E_1 was given by :

$$E_1 = E_f V_f + E_m V_m$$

At 'A' the composite strain reached the matrix failure strain ϵ_{mu} and multiple cracking of the matrix began.

During the portion of the graph 'A - B' the composite stress was almost constant, though a slight increase was discernable and this represented the zone of matrix fracture as described in the Chapter on composite theory.

Multiple fracture of the matrix ended at 'B' and from here the slope of the graph 'B - D' was defined by the composite modulus $E_1 = E_f V_f$.

The slight kink in the graph, visible at 'C' was caused by a partial failure of the composite. A break had occurred at some point of weakness (or stress concentration) but this was not sufficient to cause complete failure and the composite continued to carry increasing load.

At 'D' a major failure took place, and although the composite did not fail completely at this point further increases in load were followed by further partial failures 'E' until eventually a catastrophic failure took place 'F'.

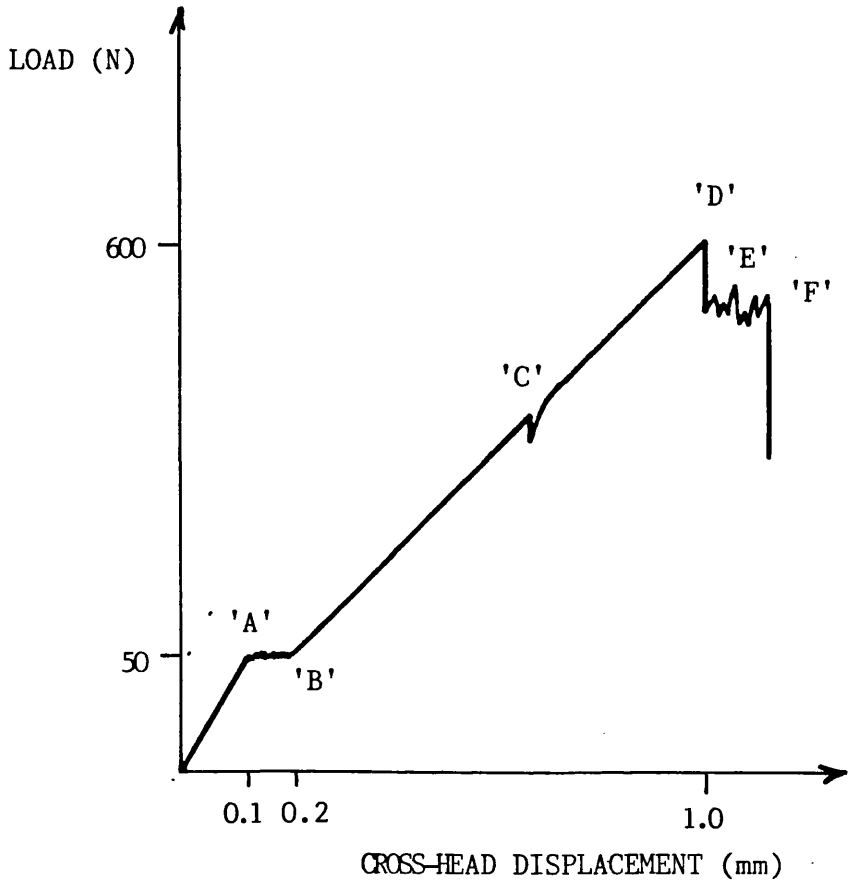


FIG. 5.4 Behaviour of Carbon fibre/PVA Prepreg under Tensile Load.

5.12 Failure Mode.

The failure modes of the prepreg samples were of two distinct types.

The first type, illustrated in Fig 5.4, was initiated by a partial failure of the sample. It was observed that this failure usually occurred close to the edge of the sample and often near to one end.

The positions at which these failures took place suggested stress concentrations within the sample rather than fibre weakness.

These initial partial failures were not catastrophic, and the initial load fall-off was followed by a period of increasing load.

Only rarely did the load sustained regain its original value before another partial failure, or total sample failure took place.

The second failure mode was typified by a perfectly smooth straight line graph from the end of the zone of multiple fracture of the matrix until a sudden and catastrophic failure took place.

This failure mode occurred less frequently than the first but it often took place at higher loads. It was usually marked by an almost explosive disintegration of the sample.

This second type of failure suggested that the prepreg sample was being loaded fairly evenly until failure stress was reached in most, or all, of the fibres simultaneously. Failure of the sample was then sudden and total.

The stress concentrations suggested by the first failure mode could have been caused by several things. Misalignment of the sample in the test rig could be a factor, or uneven fibre distribution or non-parallel fibre orientation.

Perhaps the most likely cause was the presence of some flaw in the prepreg introduced during the manufacturing process, this could have been in the form of a kink or possibly a twist.

Because the test samples were in the form of fairly wide tapes, stressing of the prepreg was not expected to be particularly even and several samples did show signs of wrinkling under load. This is typical of a fabric under test, and suggested that stress concentrations were occuring.

A flat tape, which is in effect a planar composite, is unable to redistribute stresses around fibre breaks to the same extent as a densly packed composite which has more than one plane. Therefore failure is likely to occur at lower loads.

The values of tensile strength derived from these tests were therefore not expected to accurately represent the true strength of the prepreg but to be a lower bound.

5.13 Derivation of Tensile Strength and Modulus.

a) Tensile Strength.

From the graphs of load vs. cross-head displacement produced by the test rig, the maximum load sustained by each sample of prepreg was recorded.

From the Rule of Mixtures :

$$\sigma_{1ult} = \sigma_{fult} V_f$$

If the maximum load sustained by the prepreg = P_1 , and the areas of prepreg and fibres are A_1 and A_f respectively, then the composite stress is given by :

$$P_1/A_1 = \sigma_{fult}[A_f/A_1] \qquad (5.1)$$

Therefore, the ultimate fibre tensile stress is given by :

$$\sigma_{fult} = P_1/A_f \qquad (5.2)$$

As described earlier, this value represents a lower bound for the true tensile strength of the fibres.

By comparing the ultimate fibre tensile stress (σ_{fult}), with the specified fibre strength σ_{fu}, a prepreg efficiency factor 'Q_p' can be derived, where :

$$Q_p = \sigma_{fult}/\sigma_{fu} \qquad (5.3)$$

The value of Q_p will depend upon such factors as fibre damage, and misalignment and will be in the range 0.0 → 1.0. Where 1.0 represents a perfect, undamaged sample which achieves its full theoretical tensile strength.

b) Elastic Modulus.

The initial portion of the load/extension graph prior to matrix cracking is very short and represents the prepreg behaviour only at very low stresses.

In practice the applied load is likely to be in the range represented by the straight line portion of the graph B - D in Fig 5.4.

If the fibre area = A_f and the fibre modulus = E_f then from the Rule of Mixtures :

$$E_1 = E_f V_f = E_f A_f / A_1 \qquad (5.4)$$

If two points are considered on the load/extension graph as shown in Fig 5.5 : and P_1, l_1 and P_2, l_2 are the corresponding loads and sample lengths.

Then the increase in load $\delta P = P_1 - P_2$. Therefore, the increase in composite stress is given by :

$$\delta\sigma_1 = (P_1 - P_2)/A_1$$

The increase in sample length $\delta l = l_1 - l_2$. Therefore, the increase in composite strain is given by the expression :

$$\delta\epsilon_1 = (l_1 - l_2)/L$$

Where L = gauge length of the sample.

Therefore the composite modulus E_1 is given by :

$$E_1 = \delta\sigma_1/\delta\epsilon = [(P_1 - P_2)/A_1]/[(l_1 - l_2)/L] \qquad (5.5)$$

Now, $A_1 = A_f/V_f$ and if this is substituted into Eq. (5.5)

$$E_1 = [(\delta P/A_f)/(\delta l/L)]\ V_f \qquad (5.6)$$

Therefore, the fibre modulus determined by these tests is given by the equation :

$$E_f = (\delta P/A_f)/(\delta l/L) \qquad (5.7)$$

The value of E_f derived experimentally can then be compared with the fibre modulus specified by the manufacturer and a modulus efficiency factor, 'Q_E', can be obtained.

The fibre elastic modulus derived in this way will be a lower bound for the true fibre modulus. This will be partly due to fibre damage but will also be affected by other factors.

These other factors will include such things as the elasticity of the test rig, but the dominant factor is likely to be the behaviour of the card end tabs. If these tabs distort under load then they will add to the apparent fibre extension and this will lead to an over estimate of composite strain with a consequent under estimate of composite modulus.

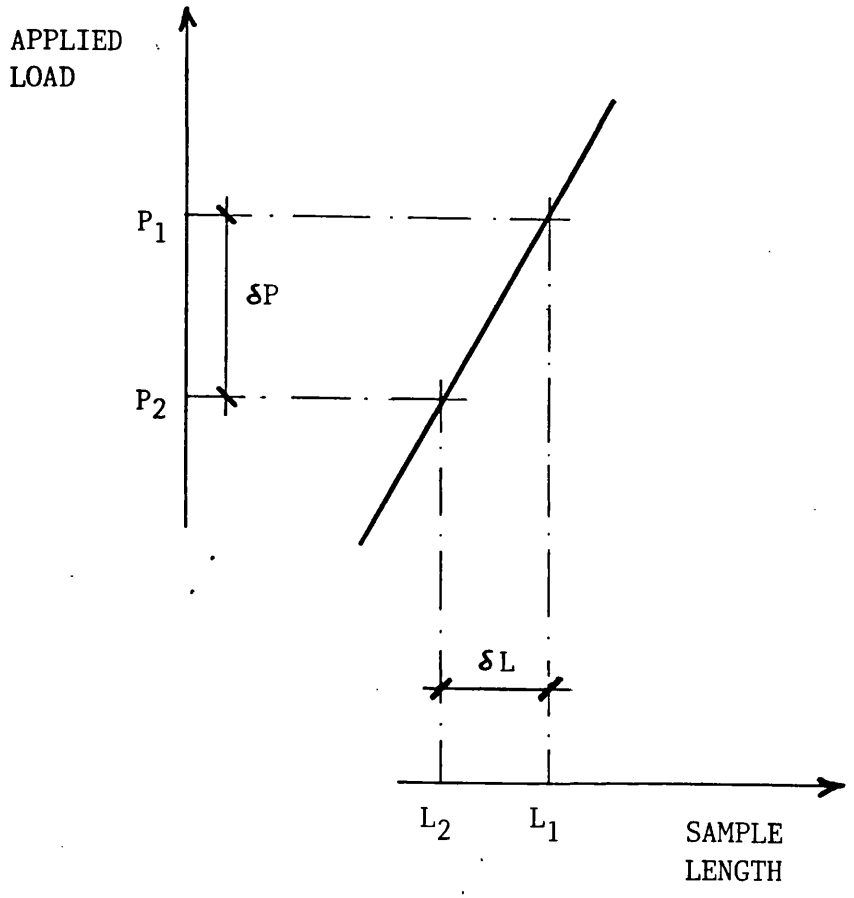


FIG. 5.5 Derivation of Prepreg Modulus.

5.14 Experimental Results.

During the course of the research programme tensile tests were carried out on over ninety samples of Carbon fibre/PVA prepreg. The results of these tests are summarized in Table 5.2. (Full details of the tests and results can be found in Appendix 7.)

From Table 5.2 the following mean values for the ultimate fibre tensile stress and elastic modulus were obtained :

σ_{fult} = 1813 N/mm^2

E_f = 108900 N/mm^2

5.15 Discussion of Results.

As expected the values for the fibre tensile strength and modulus derived from the tensile tests are lower than the true fibre properties.

The fibre properties specified by the manufacturer are :

Tensile strength = 2900 N/mm^2

Tensile Modulus = 215 - 245 x 10^3 N/mm^2

Series.	Number of Samples.	σ_{fult} (N/mm^2)	E_f (N/mm^2)
P.0	32	2096	142,325
P.3	20	1511	91,055
P.4	20	1798	100,600
P.5	20	1675	81,495
	MEAN	**1813**	**108,900**

TABLE 5.2 Summary of Results of Tensile Tests on Samples of Carbon Fibre/PVA Prepreg.

If these specified properties are compared with the results of the tensile tests the efficiency factors for strength and modulus can be derived. ie. :

Q_P = 1813/2900 = 0.63

Q_E = 108,900/215,000 = 0.51

It can be seen that the prepreg was utilising 63% of the specified strength of the fibres before failure occurred. Although this value is rather low, if the potential for fibre damage is taken into account then it is not an unreasonable lower bound.

The elastic modulus of the fibres derived from the tests appears to be only half of the specified value. This could be due to several factors but it is thought that distortion of the end tabs during testing could be an important factor.

The apparatus used for the preimpregnation process was rather crude and it is thought that this could be further improved to reduce the potential for fibre damage.

The low efficiency factors for fibre strength and modulus have an implication for the economic viability of any composite which utilises this prepreg. Carbon fibres are relatively expensive and it is essential that they are used as economically as possible if they are to compete with the alternatives.

Discussions with the composites industry have indicated that there is an accepted practical limit on the tensile strength efficiency of carbon fibre composites of approximately 80%. It can be seen from Table 5.2 that if the results of the tests on the P.0 Series of samples are analysed a tensile strength efficiency factor of 0.73 can be derived.

It is therefore considered that there should be no reason why the single tow method of prepregging could not be refined and used in a commercial situation to produce Carbon fibre/PVA prepreg with an acceptable degree of tensile strength efficiency.

CHAPTER SIX

Manufacture and Determination of the Properties of a Carbon Fibre/Cement Composite Sheet

6.1 Introduction.

The previous chapter has shown that it was possible to produce a carbon fibre/PVA prepreg of known properties using the 'single tow' preimpregnation technique and that the tensile strength efficiency of the prepreg was approximately 0.63.

The next stage of the research was to see whether it was possible to use the prepreg produced in this way to produce a carbon fibre reinforced cement composite, and to define the structural properties of such a composite.

This was done through an extensive programme of fabrication and testing which involved over a hundred individual samples of the composite material.

As it was intended that the composite material would eventually be used as tensile reinforcement for reinforced concrete structural elements the tensile properties of the composite were considered to be the most important and consequently the bulk of the test programme involved tensile tests.

In addition some flexural tests were also carried out to determine the flexural and interlaminar shear strengths of the composite.

6.2 Sample Format.

Although it was envisaged that the eventual application of the Carbon Fibre Reinforced Cement (CFRC) would involve the use of large sheets it was not considered practical at this stage to carry out tests on full scale samples as these would have been expensive in terms of materials and time and would have involved practical difficulties in testing.

For the purpose of the research a sample format was needed which was economical in its use of materials, easy to manufacture and convenient to handle and test.

The most important property of the composite material was its tensile strength and therefore the proposed sample format needed to be suitable for tensile tests.

In the preliminary tests used to determine and compare the efficiency of the pre-spread fibre and prepreg sheet formats of reinforcement, a test sample format of a CFRC composite sheet which measured 300 x 50 x 6mm thk. had been used. This format appeared to be suitable for the type of test employed.

However, it was thought that thinner samples (say 3mm) may have advantages. Firstly it was possible that failure of the thicker samples used in the earlier tests was influenced by interfacial shear stresses between the aluminium end plates and the samples. A reduction of these stresses would seem desirable.

By halving the sample thickness, the load necessary to cause tensile failure of the sample would be reduced proportionally and therefore the interfacial shear stress would be reduced. This would reduce the local effects due to the end plates and make it more likely that failure would be due to tensile stress alone.

A further practical advantage of the use of thinner composite sheets was that it would reduce the amount of material (principally prepreg) which was required. The production of prepreg in the laboratory by the 'single tow' method was a batch process and it was therefore quite slow when large quantities were required. If the amount of prepreg required was halved, this would considerably reduce the 'turn round' time for a batch of tests.

In addition, less time would be needed for the fabrication of each sample of composite sheet if the overall thickness was reduced.

The width of the sample was determined by two main factors, interfacial shear stress at the end plates and the physical limitations of the test machine.

In order to reduce the liklehood of sample failure being induced by the shear stress between end plate and sample a large area of contact is required to reduce the stresses.

The maximum width of sample was however governed by the size of the jaws on the test machine. The machine which was used for the tensile tests was an 'Instron 1195'. This had jaws which permitted a maximum sample width of 50mm.

Because of these considerations it seemed reasonable to maintain the width of the sample at 50mm, and to reduce its thickness to produce a standard sample format of 300 x 50 x 3mm thk. This format would be more economic to produce than the one used previously and would encourage tensile failure of the composite itself rather than failure of the bond between the end plates and the sample.

6.3 Composite Fabrication Methods.

The methods used for the fabrication of the samples of composite material were kept fairly simple. It was recognised that some aspects of the proceedure were rather crude but the limitations of available time limited the degree of refinement which was possible.

It was decided to form the composite samples in moulds made up from sheet perspex. This material was chosen, in preference to the plywood used earlier, for the quality of surface finish it could impart to the samples and because it would release readily without the need for mould oils.

The method of sample fabrication was basically the same for all samples and was as follows : A layer of cement paste was applied to the bottom of the mould by the use of a simple decorator's paint brush. A tow of 'single tow' carbon fibre/PVA prepreg was then laid on top of this along the axis of the mould. More cement paste was then applied by brush and the operation was repeated until sufficient prepreg had been included.

The method chosen for application of the cement paste required a reasonable degree of workability. This had to be balanced against the requirements for optimum matrix strength and a number of different water/cement ratios were used during the course of the research.

The fibre volume fraction of the composite was directly related to the area of fibre included in a single tow of prepreg and the number of tows which were included in the composite. As the cross-sectional area of carbon fibre in a single tow was known, it was possible to control the fibre volume fraction of the composite sample by controlling the number of tows which were used.

The samples were cured under a variety of conditions.

Prior to testing, the end regions of the samples were sanded smooth using an orbital sander and aluminium end plates were affixed using an epoxy resin adhesive. These end plates served to protect the samples from crushing in the jaws of the test rig.

6.4 Test Format.

The samples of carbon fibre reinforced composite were tested to failure in tension using an 'Instron 1195' test machine. The rate of loading was controlled by the speed of crosshead displacement. A cross head speed of 0.5mm/min was generally used.

Before mounting in the test rig each sample was marked with a 50mm gauge length in its centre region. A 'Wallace' optical extensometer was used to record the extension of this gauge length under test.

A graph of applied load against gauge length extension as recorded by the extensometer was automatically plotted by the test machine.

From these graphs it was possible to determine the maximum load sustained prior to failure and hence the induced stress at failure. From the slope of the graphs an estimate of the elastic modulus of the composite could be made.

6.5 Test Programme.

In order to develop and improve the carbon fibre reinforced cement composite an extensive series of tests was embarked upon.

As a result of these tests on over a hundred samples, modifications were made both to the manufacturing techniques and to the composition of the composite which improved its properties.

Because of the size of the test programme it is not practical to describe each series of tests in detail in this Chapter. Full details of test proceedures and results are given for reference in Appendix 8.

To give a clear overall picture of the test programme a summary of the important features of each test together with the mean results obtained is given in the text.

It is hoped that in this way the reader will be able to follow the progress of the research and development of the composite without becoming bogged down in the minutiae of each test series.

Group.	Test Series.	Number of Samples.
ONE	T.1	10
	T.2	10
TWO	T.3	10
	T.4	10
THREE	T.5	10
	T.6	10
	T.7	10
	T.8	10
	T.9	5
FOUR	T.11	10
	T.12	4
	T.14	10

TABLE 6.1 Summary of Test Series.

The overall test programme was divided into several groups of tests. The test series within each group were related by the nature of the composite under test.

Table 6.1 shows which test series were included in each group and how many samples were tested in each series.

The tests described here were all tensile, further tests on the flexural and interlamina shear strength of the composite are also described in 'Group 5'.

6.6 Group One.

This group of test series was used to establish the basic properties of the standard carbon fibre reinforced cement composite.

The first series 'T.1' of ten samples was made up by the method described earlier, in open perspex moulds. A cement paste with a water/cement ratio of 0.5 was used.

Seventeen individual tows of prepreg were included in each plate sample which, in theory, would give a target fibre volume fraction of 0.05 (5%).

After fabrication, the samples were cured in their moulds in 'damp' conditions under wet sacking.

Sample measurements taken prior to testing showed that in practice, a fibre volume fraction of 0.049 had been achieved.

The results of the T.1 Series were extremely disappointing. The mean tensile strength achieved was only 34.0 N/mm^2 and the mean elastic modulus was only 2117 N/mm^2. These results gave a tensile strength efficiency factor of 0.24 and a modulus efficiency factor of 0.20.

The reasons for these low results were not immediately obvious, though several possible reasons were considered.

The test samples all had a pronounced curvature which during testing would induce secondary stresses and stress concentrations around the jaws of the test machine.

These stress concentrations could cause premature failure of the samples and it was noted that failure did appear to be initiated close to the end plates, as this theory would predict.

Another factor which may have contributed to the low results was the uneven finish of the top surface of the samples. The underside face was perfectly smooth as it was formed against the perspex mould, but the top surface was left open and the surface irregularities introduced by the manufacturing process could have induced stress concentrations.

In order to assess the importance of these factors in causing premature failure a second series of tests was carried out.

In the T.2 Series of tests the perspex moulds were fitted with a perspex lid which was pressed down on top of the sample to form a smooth top surface and to apply pressure. This is illustrated in Fig. 6.1.

The cement paste used in the T.1 Series appeared to be rather wet and so for the second series the water/cement ratio was reduced from 0.5 to 0.4.

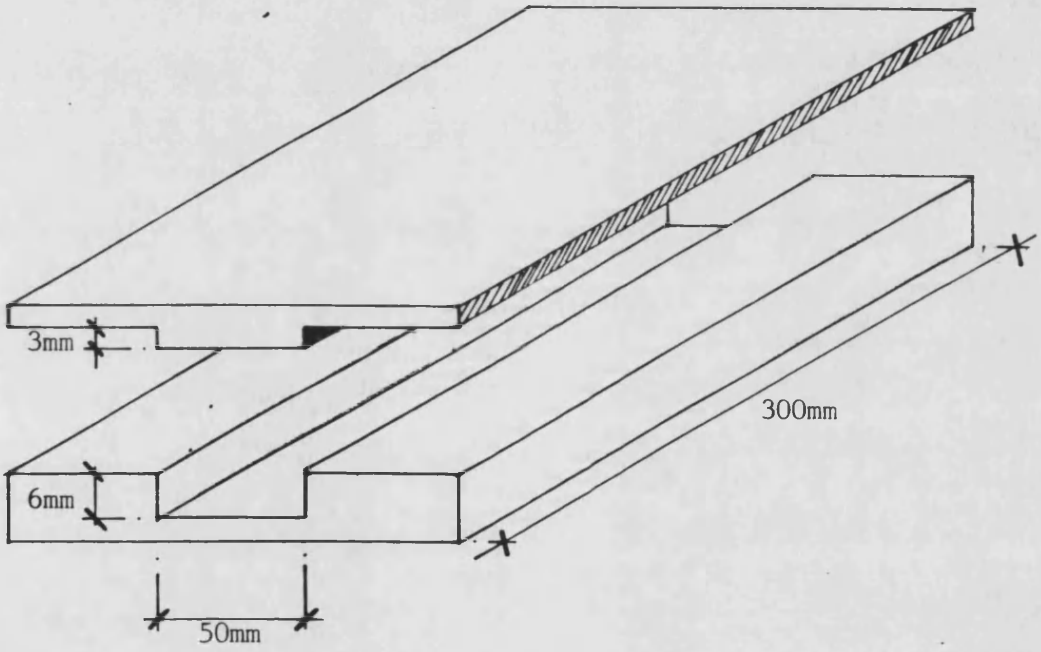


FIG. 6.1 The 'Two Piece' Perspex Mould.

Great efforts were made to try and prevent the samples curving prior to testing. For the first seven days of the curing process the samples were kept in their moulds with the lids held in place by weights. The samples were then demoulded and allowed to dry. During the drying stage weights were again applied to prevent curving.

Despite these precautions it was found that upon removal of the weights prior to testing a degree of curvature was present in all samples.

Measurement of the samples prior to testing revealed a slightly lower fibre volume fraction than the T.1 Series. The reduced value of V_f = 0.045 was possibly due to the new moulds which prevented excess cement paste from escaping when the lids are fitted, this excess paste prevented the lids from being pressed fully home and thicker samples were produced, which necessarily had lower fibre volume fractions.

A contributory factor could be the lower water/cement ratio which reduced the workability of the cement paste and its ability to flow.

The results of the T.2 series of tests indicated some improvement in composite properties with a mean tensile strength of 39.0 N/mm^2 and an E value of 8140 N/mm^2. These values gave efficiency factors of 0.30 and 0.85 respectively.

It would appear that the new fabrication techniques produced better results, though they were still rather disappointing.

Careful observation of the samples during testing indicated a possible further reason for the low failure loads.

The ends of the samples were protected in the jaws of the test machine by aluminium end plates which measured 50mm wide x 75mm long. The width of these plates matched that of the jaws and the length was chosen to reduce the interfacial shear stresses between the end plates and the sample. However, the choice of a length of 75mm resulted in the end tabs extending beyond the jaws of the test rig for a distance of approximately 25mm.

It was noted that as load was applied the end plates at point 'A' tended to curl away from the face of the sample. Pieces of the cement matrix from the face of the samples were seen to be pulled away with the plates and it seems very likely that this contributed to premature sample failure. This is illustrated in Fig. 6.2.

Most sample failures did initiate in the region of the end plates which did suggest that failure was induced by some end effect.

Examination of the samples after failure revealed some evidence of delamination within the samples. This pointed to a breakdown of the bond between the prepreg reinforcement and the cement matrix and could also explain why the tensile efficiencies were so low.

If failure was due to a combination of delamination and tensile failure, then comparison of the results with the theoretical strength in pure tension was unreasonable and the results obtained would be a lower bound for the true tensile strength if delamination had not occurred.

This series of tests proved most useful in suggesting possible reasons for the low failure loads achieved. Of particular interest were the damage caused by end plate distortion and the obvious delamination of the samples.

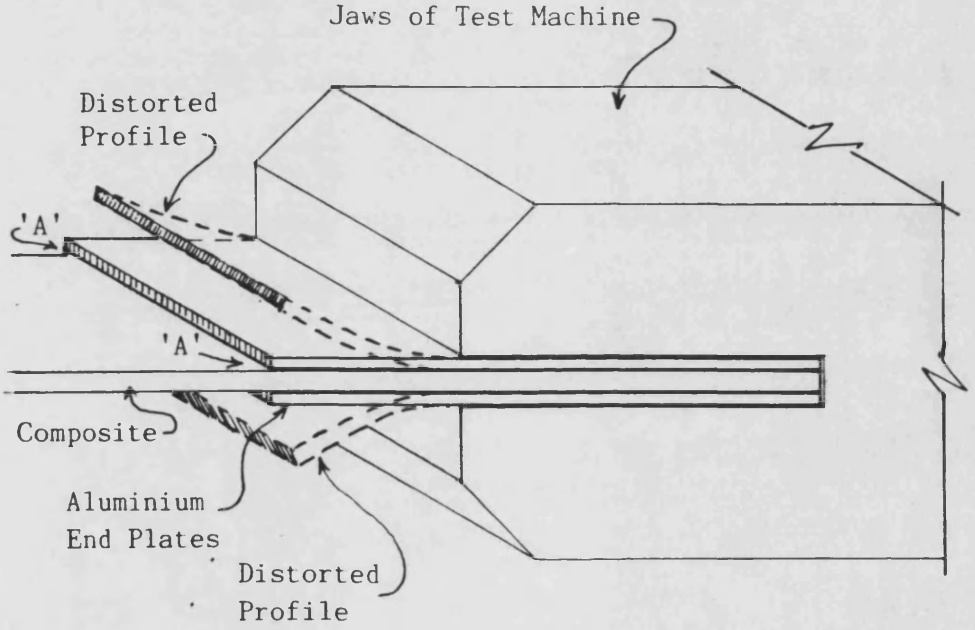


FIG. 6.2 Sample End Plate Arrangement.

6.7 Group Two.

Following on from the results of the T.2 Series, the T.3 series of tests was planned to determine whether the addition of PVA to the cement paste improved the prepreg/matrix bond and prevented delamination.

The series was also used to compare alternative end plate arrangements to discover whether the use of shorter end plates avoided the sample damage which had been observed in the T.2 Series.

The cement paste used in this series had PVA resin added to give a Resin/Water/Cement ratio by volume of 0.1 / 0.35 / 1.0 . The PVA resin used was 'Timbabond 624' which was the same as was used in the preimpregnation process.

Two different end plate arrangements were compared. A control group of four samples used the 50 x 75mm plates as used in the previous test series. A second group of four samples used end plates which measured 50 x 50mm, the shorter length meant that they were entirely contained within the jaws of the test rig.

In addition two further samples were 'necked', ie. their width was reduced in the centre region to reduce the influence of the end zones and to encourage tensile failure in the centre region of the samples. These two samples were also fitted with the smaller end plates.

As in the T.2 Series the samples were fabricated in 'closed' perspex moulds and the resulting fibre volume fraction was of the order of 0.045.

Once more, great efforts were made to prevent the samples curving, and once again they failed !

The results of the T.3 Series are given in Table 6.2.

From these results it can be seen that the samples which used the new end plate arrangement produced significantly better results than the control group using 50 x 75mm plates. It was therefore reasonable to assume that the original end plate format had made a significant contribution to the premature failure of the samples.

It was also significant that the control group itself, which had PVA added to the cement paste, performed better than the T.2 series where no PVA was added.

Examination of the samples after testing revealed no evidence of the delamination which had been present in earlier tests. This appeared to confirm that the addition of PVA to the cement paste improved the prepreg/matrix bond and resulted in higher composite strengths.

The results of the tests on the two necked samples produced apparently even better results. It should however be noted that the fibre volume fraction of the necked samples was an estimate based on the V_f of the full width of the sample before necking. It was therefore possible that a slight underestimate of the fibre volume fracton of the necked sample produced apparently superior results, the modulus efficiency factor, being greater than unity, tends to suggest an overestimate of composite properties.

The T.3 Series of tests proved most useful in clearly demonstrating the importance of the end-plate arrangement and of the necessity of good bonding between prepreg and cement matrix.

As a result of these tests and as a further control the T.4 Series of tests was carried out on samples with the 50 x 50mm end plate format, but without the addition of PVA to the cement paste.

The results of this series are also recorded in Table 6.2, these results gave a tensile strength efficiency of 0.33. This was higher than the T.2 Series, but was significantly lower than the results which had been obtained when PVA was added.

The improvement in composite strength of the T.4 Series over that of the T.2 series can therefore be entirely attributed to the new end plate arrangement .

Examination of the samples from the T.4 Series after testing revealed obvious delamination which confirmed the poor nature of prepreg/cement matrix bond when PVA was not added to the paste.

6.8 Group Three.

The Group Two test results clearly demonstrated that the addition of PVA resin to the cement paste greatly improved composite performance.

As the number of samples which had been tested in the T.3 series was limited, the T.5 series of tests was carried out to confirm these results.

The resin/water/cement ratio of 0.1 / 0.35 / 1.0 was again used as this produced a paste of reasonable workability.

T.3 Series.

Test group	Failure Stress	Strength Efficiency	Modulus. (N/mm^2)	Modulus Efficiency
CONTROL	52.0	0.39	8094	0.82
50 X 50	61.0	0.47	7622	0.80
NECKED	68.0	0.55	11648	1.26

T.4 Series.

Failure Stress	Strength Efficiency	Modulus. (N/mm^2)	Modulus Efficiency
41.0	0.33	6055	0.67

TABLE 6.2. Group Two : Summary of Results.

The aluminium end plates used in this and all subsequent test series measured 50 x 50mm to avoid the end zone damage noted earlier.

The results of the T.5 Series gave a mean tensile strength of 68.0 N/mm^2 and an elastic modulus of 9350 N/mm^2 with a fibre volume fraction of 0.047.

These values represented a tensile strength efficiency factor of 0.5 which was slightly better than the results of the T.3 Series (0.47). The elastic modulus efficiency was 0.92. The results of these tests confirmed that the addition of PVA had improved composite performance.

If these results are compared with those from the tests where PVA was not added (T.4 Series) it can be seen that the tensile strength had improved by 50%.

It was noted prior to testing that all the samples were curved to some extent and it was felt that this was bound to have an effect upon the load at which failure occurred.

It was felt that the tendancy of samples to curve could possibly be reduced by the use of thicker samples. The T.6 Series of tests was carried out using samples of an overall thickness of 6mm. Sample manufacture was carried out using the same process as before.

Although these thicker samples showed little evidence of curvature prior to testing, the results gave a tensile strength efficiency factor of 0.5 which corresponded exactly to that produced by the tests on the thinner samples.

The PVA resin which had been used as an additive to the cement paste was 'Timbabond 624' which was water soluble. It was thought that the water solubility of this resin may have a negative effect upon the long term durability of the composite if it was subjected to repeated wetting.

An alternative PVA resin, 'Timbabond 636', was available which had the property of being initially water soluble, but which became progressively less susceptible to water as it aged.

The T.7 Series of tests was performed to determine whether similar gains in composite performance could be obtained using this alternative resin as an additive to the cement paste.

Ten samples of the composite were manufactured using 6mm closed perspex moulds. It was found that the resin/water/cement ratio had to be amended slightly to 0.1 / 0.45 / 1.0 to maintain a similar degree of workability to previous series.

The results of this test series showed a reduction in composite performance. Although the fibre volume fraction was the same as the T.6 series (0.047) the tensile strength was lower at 56.3 N/mm^2 and the modulus fell to 6600 N/mm^2. These results give a tensile strength efficiency factor of 0.42 and a modulus efficiency of 0.65.

These results indicated that although the addition of '636' resin to the cement paste did give better results than when no PVA was added, the improvement in composite properties was considerably less than when '624' resin was used. It would seem that unless significant improvements in long term stability could be proved there was no other advantage to the use of '636' rather than '624'.

Apparently, although sample curvature was almost eliminated by using the thicker samples, the results of the tensile tests on these samples showed no improvement over those of the 3mm sheets.

Because of the economies in materials and fabrication time and because there was no apparent advantage in using the thicker samples it was decided to revert to using the standard sample format of 300 x 50 x 3mm thick.

It was thought that the reason for sample curvature may be found in the method of sheet fabrication.

Examination of samples of the cement sheet indicated that the distribution of the fibre reinforcement within the sample was not uniform. The layers of prepreg tended to be concentrated towards the lower half of the sample.

This could be explained by the practice of applying extra cement paste to the top of the sample during fabrication to 'top-up' the mould and ensure that the prepreg was totally covered.

As the cement paste dried, it would tend to shrink. However, the cement paste in the lower half of the samples, being constrained by the prepreg, would be prevented from shrinking. In the top half, where the prepreg was less concentrated, shrinkage would be greater and this differential shrinkage could cause the samples to curve upwards away from the bottom face.

It was noted that in practice all the samples did curve upwards in this way, which suggested some validity to this theory.

To determine whether uneven fibre distribution was a major factor contributing to sample curvature the T.8 Series of tests was carried out in which efforts were made to achieve a more even fibre distribution.

In this series, as each sample was fabricated, a thicker than normal layer of cement paste was brushed onto the bottom of the mould. Alternate layers of prepreg and cement paste were then applied as normal.

Following the results of the previous test series 'Timbabond 624' PVA resin was added to the cement paste in the ratio Resin/Water/Cement, 0.1 / 0.35 / 1.0 .

This series of tests was also used to determine whether the conditions under which the samples were cured affected the composite properties.

The test samples used in all previous test series had been cured in damp conditions, ie. stored in their perspex moulds, wrapped in wet sacking and enclosed in polythene to prevent premature drying. In this present series, five of the samples were cured using this method and the remaining five were cured in their moulds stored under water.

Examination of the samples prior to testing showed that a more even fibre distribution had been achieved. Despite this all the samples had quite marked curvature.

The results of the tensile tests showed a noticable increase in composite preformance over earlier tests. A mean tensile failure stress of 78 N/mm^2 was achieved which corresponded to a tensile efficiency factor of 0.58. (note T.5 & T.6 efficiency = 0.5).

There was no significant difference between the results of the tests on the damp cured and wet cured samples.

This series of tests seemed to indicate that although the more even fibre distribution did not prevent sample warping it did apparently improve composite performance.

This could be explained if the more even fibre distribution encouraged a more even stress distribution within the composite, this would reduce stress concentrations which could lead to premature failure.

The improvement in composite strength (16%) was quite considerable and demonstrated the importance of relatively minor variations in sample format.

It is not known why the more even fibre distribution did not reduce sample curvature as expected.

It was interesting to note at this point that, of the apparent improvements in composite performance achieved since the first test series T.1, 50 % could be directly attributed to sample format and 50 % to variations in the composite itself.

All the tensile tests so far described have tested samples at age 14 days. It was thought possible that composite strength could vary with age.

A limited series of tests, the T.9 Series, was carried out in which the samples were tested at age 41 days.

Due to an unfortunate temporary shortage of carbon fibre it was necessary to reduce the fibre volume fraction of the samples for this series to about 4.0 %.

It was found that the tensile strength efficiency of the composite was marginally higher (0.59) than the T.8 Series and the modulus efficiency was improved noticably.

It would appear that the composite performance may improve with age, though this series of tests was limited to only five samples and a much more extensive range of tests would be needed to prove this conclusively.

Test Series	Failure Stress	Strength Efficiency	Modulus (N/mm^2)	Modulus Efficiency	
T.5	68.3	0.50	9352	0.92	
T.6	68.6	0.50	9462	0.93	
T.7	56.3	0.42	6602	0.66	
T.8	70.6	0.57	8436	0.91	*(Wet cure)*
	71.2	0.58	8077	0.88	*(Damp cure)*
T.9	67.5	0.59	8262	0.97	

TABLE 6.3 **Group Three : Summary of Results.**

The results of the Group Three test series are summarized in Table 6.3. This group of tests showed that it was possible to produce a carbon fibre reinforced cement composite using PVA prepreg which had reasonable structural properties.

It also showed that the results of tensile tests on cement plates were significantly influenced by the sample format.

6.9 Summary of Composite Properties.

The tests carried out in the first three goups showed that it was possible to produce a carbon fibre/PVA prepreg reinforced cement composite sheet which had useful structural properties.

With a fibre volume fraction of only 4.5 % tensile strengths in the range 60 - 70 N/mm^2 and elastic moduli in the range 7500 - 10,000 N/mm^2 were achieved.

It was proposed that the composite material would eventually be used to provide the tensile reinforcement for in-situ reinforced concrete. At this stage of the research programme it was considered whether the composite properties attained were appropriate for this end use.

a) Tensile Strength.

The use of the composite in the form of a flat or profiled sheet on the underside of concrete structural members will provide quite large cross sectional areas of reinforcement. The tensile strength of the composite does not therefore have to be as high as traditional reinforcement which is used in quite small areas.

Consequently it was considered that a composite working stress of around 100 N/mm^2 would be reasonable. The ultimate strength required would depend upon the factor of safety which was thought necessary.

It can be seen that in order to achieve the desired stress levels the strength of the composite would have to be increased by a factor of two over the results obtained so far.

b) Tensile Elastic Modulus.

The elastic modulus of the composite was considered important as this would control the deflection of the reinforced structural member. In addition, the modulor ratio of the composite to the concrete would affect the transfer of stress into the reinforcement.

In the design of reinforced concrete structural elements the concrete is considered to have no tensile strength. The resistance to tensile stresses must therefore be provided by reinforcement. If the reinforcement used has a high modulor ratio it will attract a high proportion of the tensile stresses.

This consideration and that of limiting deflection suggested that a high composite modulus was desirable.

The elastic modulus of the traditional steel reinforcement used for reinforced concrete is around 210,000 N/mm^2. To achieve this with a carbon fibre reinforced composite using high strength fibres would require a fibre volume fraction approaching 100 %. Even if high modulus fibres were used, fibre volume fractions of around 65 % would still be needed.

To achieve a composite elastic modulus comparable with steel was obviously not feasible.

The composite modulus which had been achieved in the tensile tests was of the order of 9,000 N/mm^2. Compared to steel, this was quite low, and in fact was lower than the value usually taken for plain unreinforced concrete (around 15,000 N/mm^2).

In order to understand the implications of this it was necessary to consider what would happen if a concrete beam reinforced by such a composite was subjected to load.

As the load was applied the beam would deflect and the concrete below the neutral axis would experience tensile strain. If it was assumed that the composite sheet was well bonded to the concrete, then at the interface the strain in both materials must be equal.

If the elastic modulus of the composite sheet was lower than that of the adjacent concrete then the tensile stresses induced in the composite by this strain would be lower than those in the concrete.

At this stage therefore, the composite sheet would not be providing any reinforcement at all.

Eventually, as the load was increased, the concrete would reach its failure strain and tensile cracks would appear. At this point the tensile stress which had been resisted by the concrete would be transferred into the composite sheet across the concrete/composite interface.

The composite sheet would then be acting as reinforcement and the ultimate failure of the beam would depend upon either the tensile strength of the sheet, or the strength of the interface bond.

To summarize, if this theoretical sequence of events occurred in practice the following stages in beam behaviour under load could be expected :

1) Gradual increase in load produces corresponding increase in deflection proportional to concrete modulus.

2) Tensile cracks appear in the concrete above the composite in the centre region of the beam.

3) Continued deflection of the beam, proportional to the composite modulus.

4) Beam failure by a) Tensile failure of composite
or b) Breakdown of interface bond.

It appeared therefore, that such a composite could act as reinforcement although the deflection of the structural member would need careful consideration.

An increase in the composite modulus would obviously improve its value as reinforcement as it would then attract tensile stress from the concrete much earlier and would also reduce deflection.

In order to determine whether a composite reinforced concrete beam would in fact behave as predicted, it was decided to carry out a preliminary flexural test on a beam element reinforced with a composite sheet of similar properties to those used in the tensile tests.

6.10 Behaviour of a Composite Reinforced Concrete Beam.

A carbon fibre reinforced cement composite sheet, measuring 2.3 metres long x 150mm wide x 6mm thick was made up using the hand lay-up techniques used for the tensile samples described earlier. Eighty two individual tows of prepreg were used to give a target fibre volume fraction for the plate of 4.0 %, in practice the fibre volume fraction achieved was approximately 3.5%. Timbabond 624 PVA resin was added to the cement paste to give a Resin/Water/Cement ratio of 0.1/0.35/1.0.

At age 14 days, the composite sheet was placed in the bottom of a beam mould and after a cement slurry had been applied to its top surface the concrete was poured.

The concrete was placed in layers, each approx 50mm thick and each was well vibrated before the next was applied. When the mould was full, the top of the beam was trowelled smooth.

The beam, which measured 2250 x 150 x 150mm was stored in its mould for 26 days. During this time it was kept constantly damp.

The beam was tested in three point bending over a span of 2.0m at age 28 days. The test arrangement is illustrated in Fig 6.3. (Note : the dark patches seen on the beam are rust staining from the steel beam mould.)

Unfortunately, the only test machine available for samples of this size was an 'Avery - Denison' with a max load capacity of 100 Tonnes. To use this machine was really the equivalent of using the proverbial sledge hammer to crack a nut as the expected failure loads of the composite reinforced beam lay at the very lowest end of the machine's range. Consequently the sensitivity of the machine and its accuracy at this level of load could be open to question.

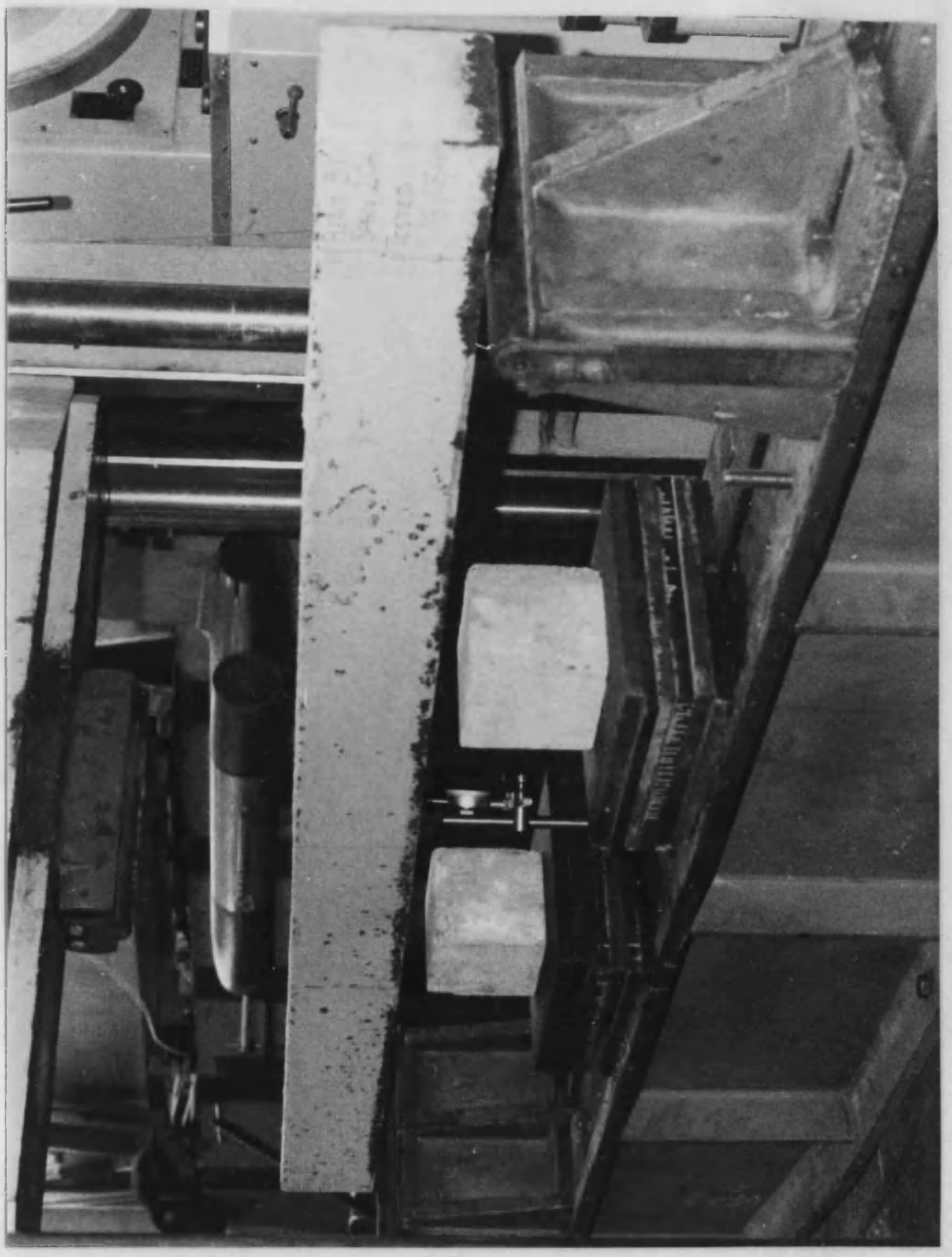


FIG. 6.3 Preliminary Composite Reinforced Beam Test.

A full scale load range of 50 KN was selected and the load was applied in increments of 2.0 KN. At each load stage the mid-point deflection of the beam was measured using a dial guage.

The load stages and corresponding deflections are recorded in Table 6.4.

As the beam was loaded beyond 8.0 KN several cracks were heard, Tension cracks were then noticed in the concrete and almost simultaneously a delamination crack appeared at the interface between the concrete and the composite plate.

The rate of deflection increased markedly and the tension and delamination cracks spread rapidly until total failure of the beam occurred.

At failure the concrete broke completely in two at the point of application of load and one half of the beam completely delaminated from the composite plate. The remaining half suffered delamination for approximately 50 % of its length from the centre towards the support.

Analysis of the results showed that beam failure took place when the tensile stress in the composite was approximately 31.0 N/mm^2 and the interfacial shear stress was 0.21 N/mm^2.

This preliminary test seemed to confirm the predicted beam failure mode described earlier. The strength of the structural element was limited by the strength of the interface and this broke down when the tensile stress in the plate had reached only approximately 50 % of its predicted ultimate strength.

Load (KN)	Deflection. (mm)
0.0	0.0
2.0	0.0
4.0	0.02
6.0	0.21
8.0	0.46
9.2	*-FAILURE-*

TABLE 6.4 Results of a Preliminary Flexural Test on a Composite Reinforced Concrete Beam.

A factor which may have contributed to the premature failure of the beam was the rapid stress transfer from concrete to composite which took place when the concrete reached its failure strain. This 'cross-over' effect could be alleviated by a higher composite modulus which would attract more load into the composite plate earlier and would thus avoid this rapid loading.

For this to take place the composite modulus must be equal to or greater than the modulus of the concrete. As the composite modulus is directly related to the modulus of the fibres and the fibre volume fraction, this relationship defines a minimum value of fibre volume fraction.

From the earlier predictions and from the results of this preliminary test it would seem that a higher composite modulus was desirable.

The necessary increase in composite properties could be achieved by an increase in the fibre volume fraction or by the use of a fibre type with improved properties.

The next group of tests which was carried out studied the effects of using higher fibre volume fractions to achieve improved composite performance.

6.11 Group Four.

Following on from the results of the preliminary beam test further tensile tests were carried out on composite samples.

The T.11 Series of tests on ten samples, was carried out to determine whether an increase in fibre volume fraction produced the corresponding improvement in composite performance which would be expected from the Rule of Mixtures.

The standard sample format was used (300 x 50 x 3mm), but the number of prepreg tows used in each sample was increased from 17 to 40 tows.

Because of the higher fibre content a higher degree of workability was required of the cement paste and therefore the water cement ratio was increased to give a Resin/Water/Cement ratio of 0.1/0.45/1.0.

Higher failure loads were expected and it was possible that these would induce interfacial shear failure in the grip zones prior to tensile failure of the samples.

To reduce this risk, and to encourage tensile failure, six of the samples in this series were 'necked' down to 25mm in their centre region.

In practice this proved to be unnecessary as interfacial shear failure between the end plates and the composite did not occur, even in the un-necked samples.

The fibre volume fraction which was achieved was around 0.09 (9.0%), which was twice that used previously. The tensile failure stress of the composite was increased to about 120 N/mm^2 and the elastic modulus to 19,000 N/mm^2.

see Table 6.5

These results gave a mean tensile strength efficiency factor of 0.47 and a mean modulus efficieny of 0.96.

Examination of the failed samples after testing revealed some evidence of delamination within the composite, indicating a breakdown of the prepreg/matrix bond.

This could have contributed to the premature failure resulting in the reduced efficiency factors.

As mentioned earlier, to increase the workability of the cement paste additional water was added. No corresponding increase in the quantity of PVA was made and it was possible that the increase in the water/PVA ratio had reduced the effectiveness of the PVA in improving the prepreg/cement matrix bond.

To determine whether the relative decrease in PVA content had in fact adversly affected the composite performance a further limited series of tests was carried out.

The T.12 Series of tests used four samples with a fibre volume fraction of 0.91. The water/cement ratio was the same as that used for the T.11 Series but the resin/water ratio was increased so that the overall proportions of the cement paste mix were in the ratio resin/water/cement 0.13/0.45/1.0. The resin/water ratio was therefore the same as had been used in the earlier test series where delamination had not occurred.

The mode of failure of the samples suggested that some delamination was still taking place, but the composite performance achieved was better than the T.11 Series.

A composite tensile strength of 137 N/mm^2 was obtained with an elastic modulus of 18,600 N/mm^2. These results gave a tensile strength efficiency factor of 0.52 and a modulus efficiency of 0.95.

From a comparison of these results with those from the T.11 Series it could be seen that the modulus efficiency of the composite was virtually unchanged but that the tensile strength efficiency had increased by approximately 10 % .

From these results it could be deduced that the proportion of PVA in the cement paste was an important factor in determining composite strength.

It was possible that as these samples did show some evidence of delamination having occurred, that a further increase in PVA content may further improve the composite properties.

With this possibility in mind, a further series of tests, the T.14 Series was carried out on ten samples which were made up using a cement paste in which the PVA content had been raised by 50 %. The fibre volume fraction of the resulting samples was slightly lower than previously, at approx. 8.0 %.

This was due to the PVA rich cement paste having a thicker consistency resulting in thicker samples.

Tensile strengths and elastic moduli of 103.0 N/mm^2 and 16,000 N/mm^2 respectively were recorded which corresponded to efficiency factors of 0.45 for strength and 0.94 for modulus.

These results appeared to show that the increased proportion of PVA resulted in a lower tensile strength efficiency factor and a virtually unchanged modulus efficicency.

The three test series in which the PVA content of the cement paste has been varied, showed that the best composite properties were achieved with a Resin/Water/Cement ratio of 0.13/0.45/1.0. Both an increase in resin content and a decrease seemed to result in lower tensile strength efficiency factors.

A summary of the results of these three test series is recorded in Table 6.5 .

Whether this ratio of constituents, which was originally arrived at almost accidentally, is the optimum for tensile strength is not immediately obvious, and a much wider range of tests would be required to determine the true optimum ratio for composite performance.

This group of tests has proved that, as predicted, the composite performance could be improved by increasing the fibre volume content.

The increase in tensile strength is slightly less than the strictly proportional relationship of the Rule of Mixtures would suggest as indicated by the lower efficiency factor of 0.52 (T.12 Series) compared to a maximum of 0.59 achieved with the lower volume fractions.

Tensile strengths upto 137.0 N/mm^2 were achieved, which is very encouraging and these were certainly of a high enough order for pratical use.

Tensile moduli of over 19,000 N/mm^2 were obtained. This is higher than plain concrete (15,000 N/mm^2) and this should result in a more gradual transfer of stress to the reinforcement when used in concrete members.

Even higher moduli may be required to limit beam deflection, this could be confirmed by practical tests. However, it was felt that it would be difficult to significantly increase the fibre volume fraction above the 9.0 → 10.0 % achieved and therefore, any further increase in composite modulus could only be achieved by the use of higher modulus fibres.

Test Series	Failure Stress	Strength Efficiency	Modulus (N/mm^2)	Modulus Efficiency
T.11	129.2	0.47	19596	0.96
T.12	137.0	0.52	18611	0.95
T.14	103.4	0.45	16001	0.94

TABLE 6.5 Group Four : Summary of Results.

Such a fibre, 'Grafil HM-S' manufactured by Courtaulds UK Ltd, has a tensile modulus in the range 320,000 - 355,000 N/mm^2. If these fibres were used and a proportional increase in composite modulus was achieved, then composite tensile moduli of the order of 28,000 - 30,000 N/mm^2 could be expected.

It was intended to confirm this in a series of practical tests, but the time available for such work expired and no further practical work to assess the tensile properties of the composite was possible.

6.12 GROUP FIVE.

The previous groups of tests have only considered the behaviour of the composite material under tensile loads. In this group the flexural properties of the composite were considered.

It was thought that the ultimate strength of the composite may be limited by the strength of the bond between the prepreg and the cement. This was confirmed by the results of those test series where PVA was not added to the cement paste and delamination occurred.

It was decided to try and evaluate this bond strength by a determination of the interlaminar shear strength of the composite.

A series of tests was carried out in which horizontal shear stress was induced in a number of samples by testing in three - point bending over short spans.

The composite sheet samples measured 100mm long, and were 50 mm wide x 6 mm thick, each sample contained 70 individual tows of prepreg. The samples were tested over a span of 80mm.

An 'Instron 1122' test machine was used to apply a central point load. The rate at which load was applied was controlled by the speed of cross head displacement which was set at 0.5 mm/min.

The samples were loaded continuously until failure occurred, which was marked by a sudden fall off in recorded load. A graph of load against cross head displacement was automatically recorded by the test rig and a fairly typical example of composite behaviour under test is illustrated in Fig. 6.4.

If it is assumed that horizontal shear failure takes place on a flat plane at the level of the neutral axis then it can be shown that the horizontal shear stress (v_h) at the maximum load P_{max} is given by the formula :

$$v_h = \tfrac{3}{4} P_{max}/(b.d)$$

where b = sample width and d = sample depth.

Using this formula, and substituting for the sample dimensions in each case the results given in Table 6.6 were obtained.

The mean interlaminar shear stress for the composite obtained by this method was quite high at 3.2 N/mm^2 which suggested that interlaminar shear failure of the material should not be a problem.

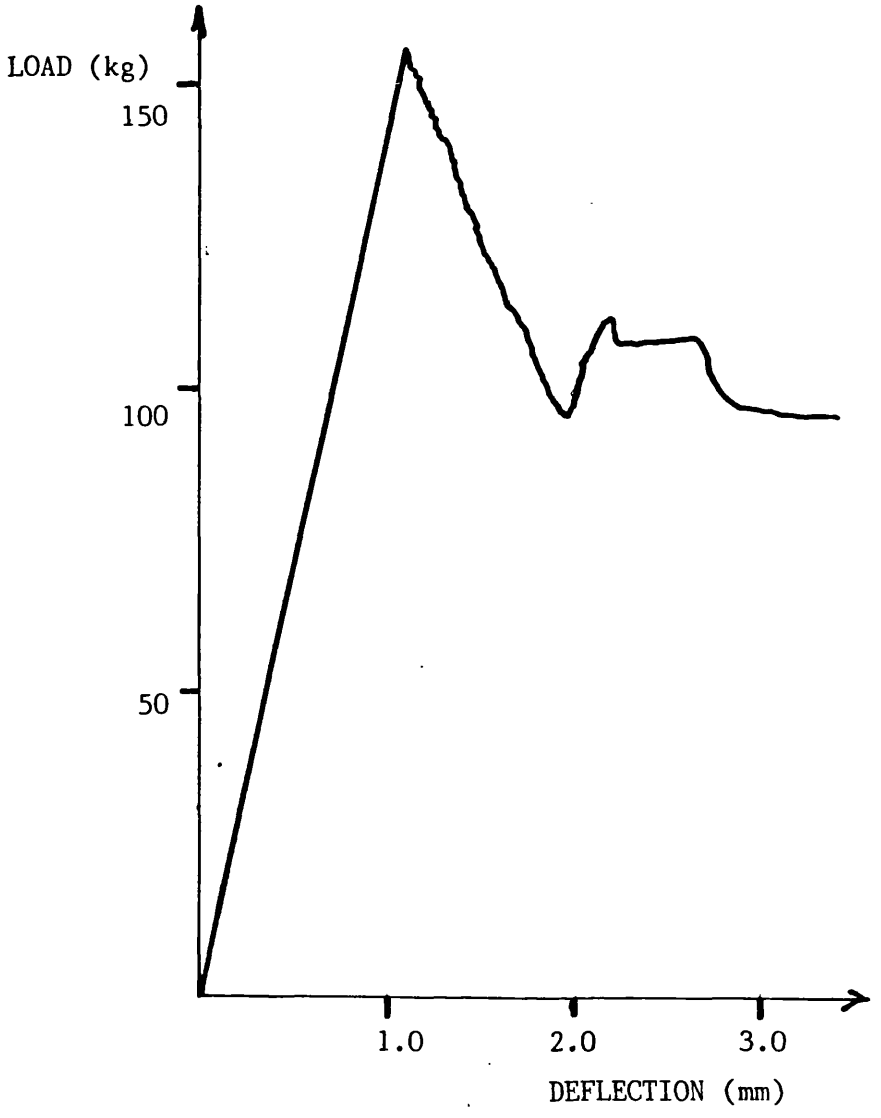


FIG. 6.4 Flexural Behaviour of CFRC Composite.

The results of these tests will be an upper bound for the true interlaminar shear strength as two important assumptions were made which do not necessarily hold true in practice. The first of these was that failure takes place at the neutral axis, and the second was that the failure surface was perfectly flat.

The second of these assumptions was almost certainly not true in practice as the composite was not a planar laminate, but had many layers of prepreg and cement which did not necessarily lie in flat planes. Any horizontal failure surface would therefore be unlikely to be perfectly flat, but would follow the various planes of the prepreg tows.

In addition to the interlaminar shear strength, the flexural strength of the composite was also considered to be important because of the proposed end use. This required that the composite would act both as a system of permanent shuttering and as tensile reinforcement for concrete elements.

In order to act as formwork the composite must be capable of supporting the weight of the wet concrete until it has hardened and becomes a reinforced element.

It is also important that the formwork does not deflect excessively under the weight of the concrete. Deflection could be limited in several ways, by close centre propping, by the use of thick section composite sheets, or by the use of a profiled cross section.

Sample Number	Failure Load(N)	Sample Width	Sample Depth	v_h (N/mm^2)
.01	1692	50.5	6.45	3.90
.02	1368	49.8	6.73	3.06
.03	1265	49.5	6.57	2.92
.04	1305	49.8	6.58	2.99
.05	1560	50.5	6.82	3.40
.06	1278	50.5	6.64	2.86
.07	1540	50.3	6.68	3.44
.08	1579	50.8	6.92	3.37
.09	1447	51.0	6.85	3.10

TABLE 6.6 Interlaminar Shear Strength of CFRC Composite.

Of these alternatives the first would increase the cost of the system and the time needed to erect it, the second would increase the weight and cost of the composite sheet with no long term advantage whereas the third, the use of profiled sheets, could allow the use of fairly thin sections which would retain their rigidity through the corrugations. It would seem that the use of a profiled format could offer the most advantage.

6.13 Analysis of a Profiled Section.

In order to determine the suitability of a profiled section for use as permanent shuttering a theoretical analysis was carried out. For the purpose of this analysis the section profile illustrated in Fig. 6.5 was assumed.

The tensile properties of the composite material were based upon the results of the T.12 Series of tests in Group Four which had an ultimate tensile strength of 137.0 N/mm^2.

From Fig. 6.5, the Moment of Resistance of the section per metre width (based upon the tensile strength of the composite) was given by :

$$MR = \sigma_t (b.t) d/x$$

$$= 137\ (100x3)100/0.3$$

$$= 13.7\ KNm.$$

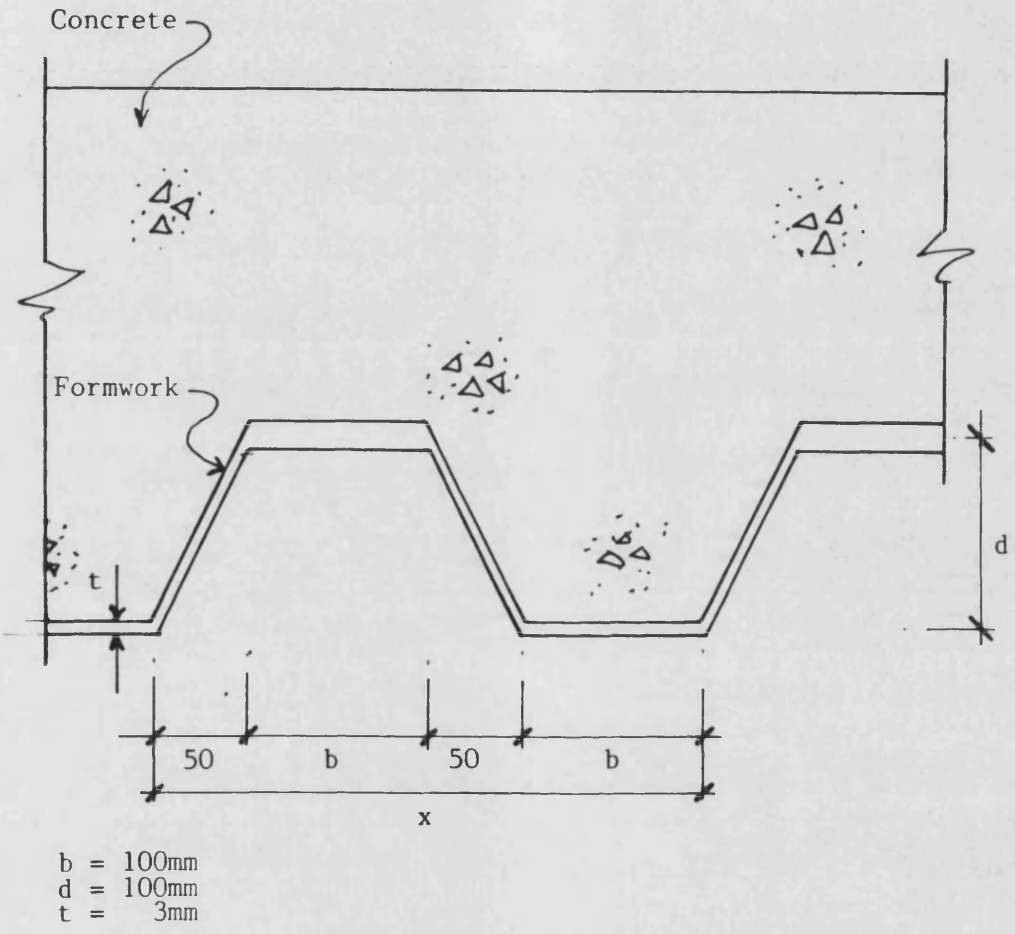


FIG. 6.5 Proposed Section of Profiled Composite Formwork.

The compressive strength of the composite is not known, it is likely to be considerably less than the tensile strength and therefore the Moment of Resistance of the section may be governed by the compressive strength of the composite. Premature failure of the section due to compressive stress could be avoided by increasing the area of the upper flanges of the section.

For the purpose of this analysis it is assumed that the compressive flanges of the section are sufficiently large so that tensile stress governs.

The depth of concrete to be supported was assumed to be 250mm with a density of 24.0 KN/m^3. It was further assumed that the shuttering would be propped at 2.0m centres. The moment due to the applied load was therefore given by :

$M_a = 0.25(24.0)x(2.0)^2/8$

$= 3.0$ KNm.

The moment of resistance of the section was clearly in excess of the applied moment, with a factor of safety of $13.7/3.0 = 4.5$.

This simple analysis showed that such a profiled section would be capable of supporting the weight of the poured concrete until it could act together with the set concrete as a composite reinforced element.

CHAPTER SEVEN

Analysis of the Composite Material

7.1 Introduction.

In order to be able to assess the performance of the composite material and to predict its behaviour a theoretical model was developed which could be used to represent the actual composite.

In the construction of this model, several simplifying assumptions were made. The validity of these assumptions, and the importance of any errors which may have been introduced due to the simplicity of the model were considered.

7.2 The Composite Model.

The carbon fibre reinforced cement, in the sheet form in which it was produced, was considered to be a two-phase composite, consisting of carbon fibres and a hardened cement paste matrix.

The carbon fibres were considered to be continuous, and to be aligned parallel with the direction of the applied load. The fibres were assumed to be distributed throughout the matrix in a regular array.

Such a composite is illustrated in Fig. 7.1

In the construction of this model the presence of the PVA resin, both in the prepreg and in the cement matrix was ignored.

The result of ignoring the presence of the PVA was that it was in effect considered as part of the cement matrix and was included within the matrix volume fraction.

This could be quite significant as the resin volume fraction of the prepreg had previously been estimated at 0.75 (Table 5.1). A composite fibre volume fraction of 0.10 would therefore represent a PVA resin volume fraction of 0.30.

The structural properties of the PVA resin were not known.

It was thought that although to neglect the presence of the PVA could be significant in consideration of the composite behaviour at low stresses, it would be reasonable to assume that at the working stresses of the composite in use, the failure stress of both the cement and the PVA would have been exceeded and therefore, the composite behaviour would depend solely upon the properties of the fibre reinforcement.

The omission of the PVA component from the composite model would not therefore affect the prediction of the modulus under working load or of the ultimate composite tensile strength.

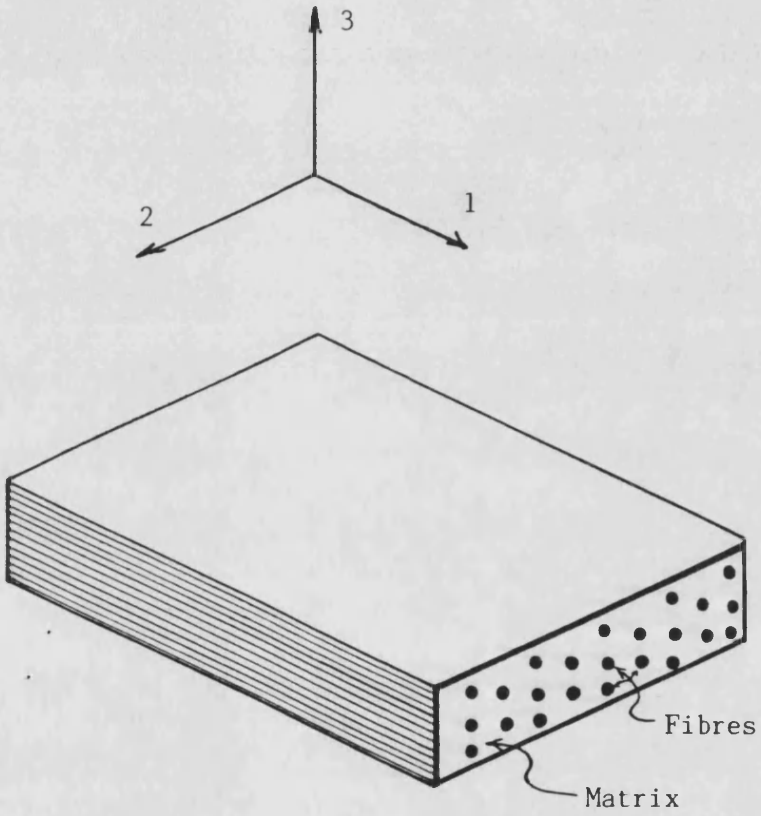


FIG. 7.1 Theoretical Composite Model.

7.3 Component Properties.

The carbon fibres used in this research were manufactured by Courtaulds Uk Ltd from a Pan precursor and were of the type designated 'Grafil XA-S'.

The properties of these fibres, as specified by the manufacturer[42], are given in Table 7.1.

The fibre properties were derived by the manufacturer from the results of tensile tests on samples of carbon fibre tows, preimpregnated with an epoxy resin[44]. A gauge length of 150mm was used.

The structural properties of cement paste are extremely variable. They depend upon several factors, the most important of which is considered to be the water/cement ratio. Other factors which may influence cement paste properties are the presence of voids and the curing conditions.

Properties of a typical hardened cement paste of water cement ratio 0.35 are given in Table 7.2.

These properties were derived from several sources[43][45] and were taken as a reasonable basis for the prediction of composite behaviour.

As it was considered that the properties of the cement matrix would only be of importance in the lower stress ranges the values given in Table 7.2 were thought to be sufficiently accurate.

Property.	Specification.
Tensile Strength.	2900 N/mm^2 (Min.)
Tensile Modulus.	215000 - 245000 N/mm^2
Failure Strain.	1.5 %

TABLE 7.1 Properties of 'Grafil XA-S' Carbon Fibre.

Property.	Specification.
Tensile Strength.	5.5 N/mm^2
Tensile Modulus.	14000 N/mm^2
Failure Strain.	0.5 %

TABLE 7.2 Properties of Hardened Cement Paste.

7.4 Theoretical Composite Properties.

Using the properties of the components defined in Tables 7.1 & 7.2, it was possible to derive the theoretical composite properties by applying the Rule of Mixtures equations.

It will be recalled that the Rule of Mixtures depended upon several assumptions, the principle ones being :

1) Matrix and fibre behave elastically.
2) Equal strain in fibre and matrix.

There were two stages in the behaviour of the composite which had to be considered. First : before the matrix had reached its failure strain, and second : after failure of the matrix.

a) Composite Properties Prior to Matrix Failure.

From the Rule of Mixtures, the composite modulus E_1 was given by:

$$E_1 = E_f V_f + E_m(1 - V_f)$$

The minimum specified fibre modulus of 215,000 N/mm^2 was substituted for E_f and a value of 14,000 N/mm^2 for E_m. A range of composite moduli could then be plotted for varying fibre volume fractions V_f. This is shown in Fig. 7.2

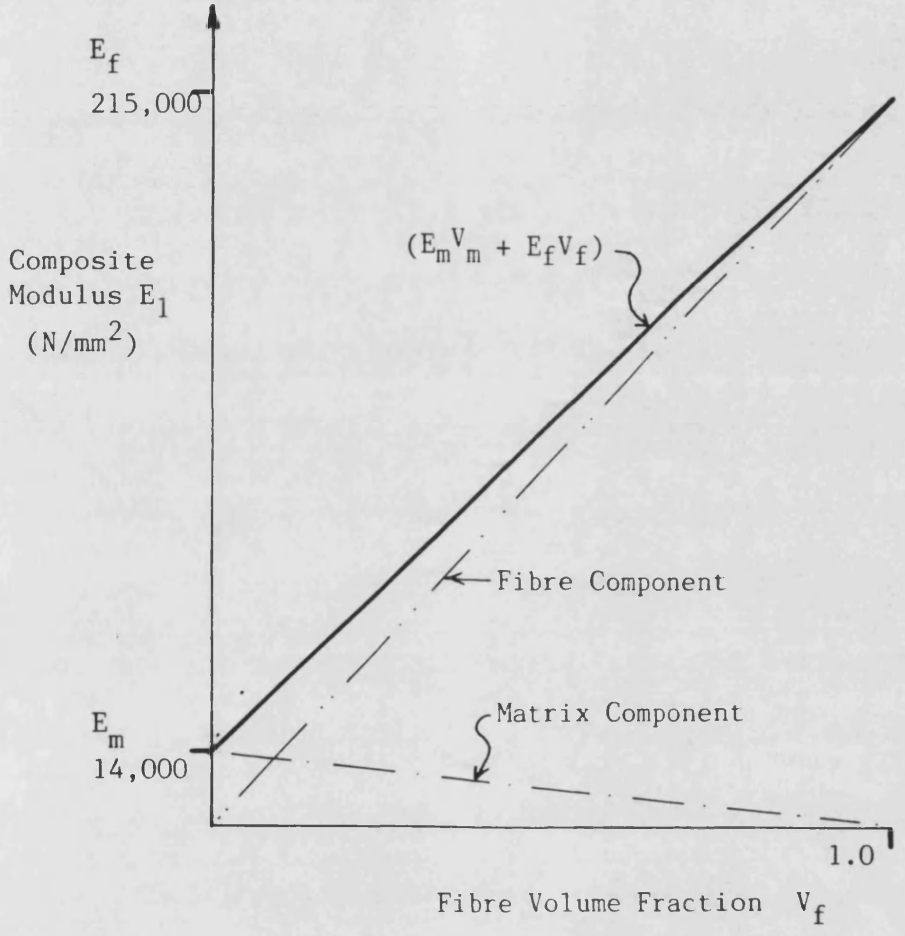


FIG. 7.2 Properties of Carbon Fibre Reinforced Cement Composites. (Pre Matrix Cracking).

The composite stress σ_1 was similarly given by the equation :

$$\sigma_1 = (E_f V_f + E_m V_m)\epsilon_1$$

Based on the assumption of equal strain, the stress in each component could be derived from the relationships :

$$\sigma_f = E_f \epsilon_1 \quad \text{and} \quad \sigma_m = E_m \epsilon_1$$

b) Composite Properties After Matrix Failure.

It was assumed that the composite strain had exceeded the failure strain of the matrix, ϵ_{mu}, and that the composite properties were therefore related solely to the fibre properties.

The expression for the composite modulus therefore became :

$$E_1 = E_f V_f$$

The composite elastic modulus after matrix cracking had occurred was thus lower than at low strains as there was now no matrix component.

After matrix cracking, the stress in the composite was given by :

$$\sigma_1 = \sigma_f V_f$$

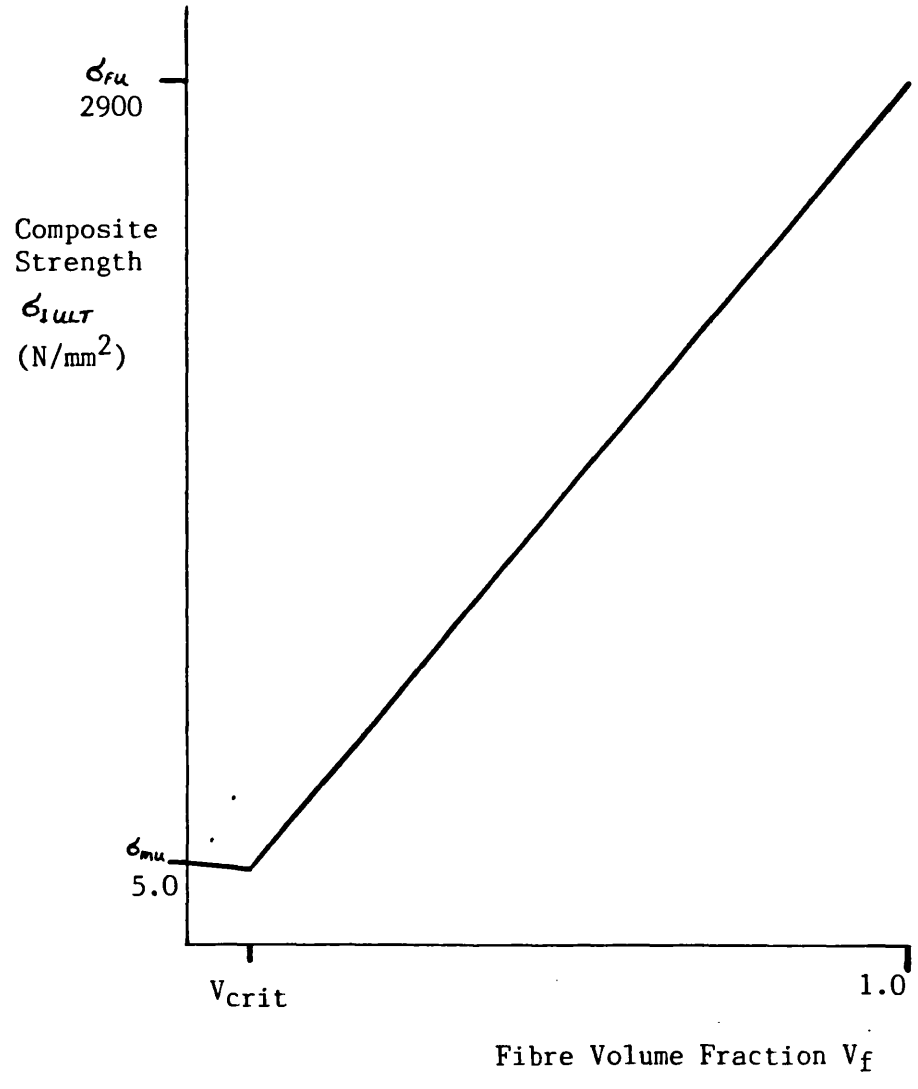


FIG. 7.3 Ultimate Tensile Strengths of Grafil 'XA-S' Composites.

The ultimate composite tensile strength was defined by :

$$\sigma_{cu} = \sigma_{fu} V_f$$

Where σ_{fu} = tensile strength of fibres.

The theoretical ultimate composite strengths of composites of various fibre volume fractions using Grafil 'XA-S' fibres are compared in Fig. 7.3

It should be realised that σ_{cu} was an upper bound for the actual composite strength. If composite failure was due to some other mechanism such as delamination, then the actual composite stress at failure would be less than the value given by that expression.

7.5 Overall Composite Behaviour.

The Rule of Mixtures predicts that the behaviour of a carbon fibre reinforced cement composite will follow the line of the stress/strain graph plotted in Fig. 7.4.

For example, if such a composite is considered which has a fibre volume fraction of 0.09, with the component properties :

E_f = 215,000 N/mm^2

E_m = 14,000 N/mm^2.

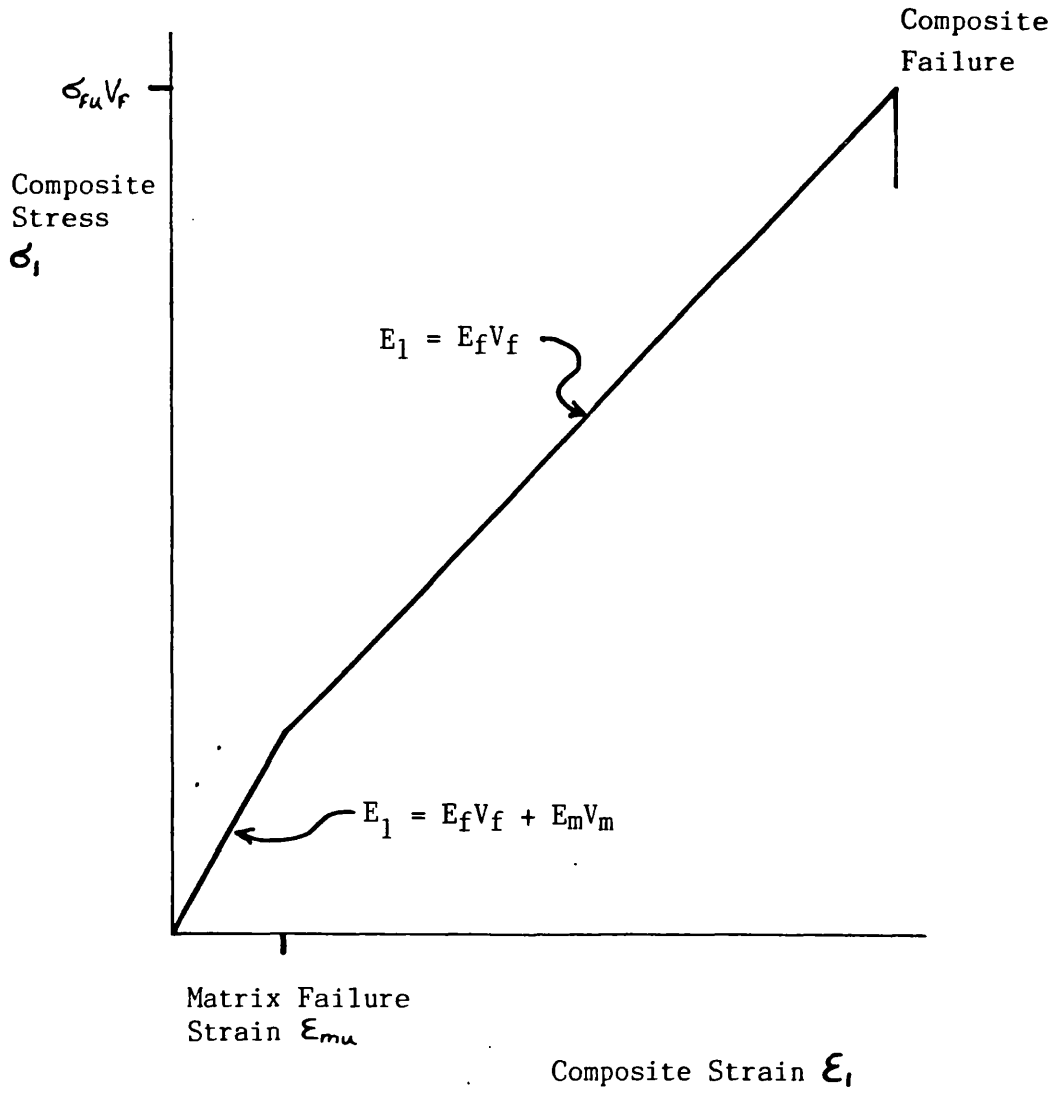


FIG. 7.4 Theoretical Behaviour of a CFRC Composite.

Then the expressions for the composite properties derived from the rule of mixtures are :

Pre ϵ_{mu} modulus. $E_1 = 32,090$ N/mm^2

Post ϵ_{mu} modulus. $E_1 = 19,350$ N/mm^2

Ultimate tensile strength. $\sigma_{1u} = 261.0$ N/mm^2.

7.6 Comparison of Composite Behaviour with The Theoretical Model.

In the previous section the properties of the carbon fibre reinforced cement sheet were predicted by application of the Rule of Mixtures.

In this section, the values of composite strength and modulus derived from the test programme, described in Chapter 6, were compared with these theoretical predictions.

The composite performance was assessed from efficiency factors derived by a comparison of theoretical and experimental properties.

For example, for Tensile Strength :

Actual composite strength = σ_{1ult} *(From test results.)*

Theoretical composite strength = $\sigma_{fu}V_f$ *(Rule of Mixtures.)*

The tensile strength efficiency factor 'Q_t' was given by :

$$Q_t = \sigma_{1u1t}/\sigma_{fu}V_f$$

Similar efficiency factors can be derived for the composite modulus.

a) Tensile Strength.

A summary of the mean ultimate composite strengths for each test series are given in Table 7.3. The test series were in three main categories :

a) Low V_f - no PVA added to cement paste.

b) Low V_f - PVA added to cement paste.

c) High V_f - PVA added to cement paste.

In each case the theoretical composite strengths $\sigma_{fu}V_f$ and the tensile strength efficiency factors are given.

From Table 7.3 it can be seen that the highest tensile strength efficiency factor was obtained in the T.9 Series (0.59) with a fibre volume fraction of 0.4. The highest recorded mean composite strength was for the T.12 Series (137.00 N/mm^2) with a fibre volume fraction of 0.91 .

Category	Series No.	V_f	Tensile Strength. (N/mm^2)	$\sigma_{fu}V_f$ (N/mm^2)	Efficiency Factor
a)	T.1	0.049	34.0	142.1	0.24
	T.2	0.045	39.0	130.5	0.30
	T.4	0.043	41.0	124.7	0.33
b)	T.3	0.045	61.0	130.5	0.47
	T.5	0.047	68.3	136.3	0.50
	T.6	0.047	68.6	136.3	0.50
	T.7	0.047	56.3	136.3	0.42
	T.8	0.043	71.0	123.9	0.58
	T.9	0.040	67.5	114.8	0.59
c)	T.11	0.095	129.2	275.5	0.47
	T.12	0.091	137.0	263.9	0.52
	T.14	0.080	103.4	232.0	0.45

TABLE 7.3 Summary of Tensile Strength Results..

b) Tensile Modulus.

The elastic modulus for the composite samples was derived from the straight-line portion of the graph after matrix cracking had occurred.

A summary of the elastic moduli for each test series is given in Table 7.4. As before, the test series are divided into the categories a, b, & c .

The highest composite modulus efficiency factor was recorded for the T.9 Series (0.97). The second highest modulus efficiency factor was recorded for the T.11 Series (0.96).

c) Discussion of Results.

Comparison of the experimental results with theory showed that the full theoretical potential of the carbon fibres was not being utilised.

This could be attributed to two important factors : fibre damage and breakdown of the fibre/matrix bond.

Fibre damage was likely to be significant as carbon fibres are extremely delicate and are very susceptible to damage. At any point in the fabrication process where handling occurred fibre damage was also likely to occur. As was seen earlier, a significant amount of damage was possible during the pre-pregging process and more could occur during the fabrication of the cement plates themselves.

Category	Series No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
a)	T.1	0.049	-	10535	-
	T.2	0.045	8140	9675	0.85
	T.4	0.043	6055	9245	0.67
b)	T.3	0.045	7622	9675	0.80
	T.5	0.047	9352	10105	0.92
	T.6	0.047	9462	10105	0.93
	T.7	0.047	6602	10105	0.66
	T.8	0.043	8200	9245	0.90
	T.9	0.040	8262	8600	0.97
c)	T.11	0.095	19596	20425	0.96
	T.12	0.091	18611	19565	0.95
	T.14	0.080	16001	17200	0.94

TABLE 7.4 Summary of Elastic Modulus Results.

Tests on samples of prepreg tape, described in Chapter 5, resulted in a mean tensile strength efficiency factor for the prepreg of 0.63. This demonstrated that, even before incorporation into the composite sheet, the tensile strength of the prepreg was apparently much less than theory would predict for undamaged fibres.

If the strength of the prepreg tows had been reduced by fibre damage prior to their incorporation into the cement composite, then the comparison of composite properties with theoretical values based on undamaged fibres was unreasonable.

Breakdown of the fibre/matrix bond would result in delamination of the composite and premature failure of the samples.

This type of failure was observed, particularly in those samples where PVA resin had not been included in the cement paste.

If delamination of the sample occurred then the recorded failure stresses would not represent the tensile strength of the reinforcement, but would be related to the strength of the prepreg/matrix bond.

If the ultimate failure of the composite was solely related to the degree of fibre damage, then it would be expected that the values of tensile strength effficiency and modulus efficiency would be similar.

If ultimate composite failure was occurring through a mechanism other than pure tension then it could be expected that the modulus efficiency factor would represent the degree of fibre damage, but that the tensile strength efficiency factor would be governed by the mechanism causing failure.

From the summary of results it can be seen that in all cases the elastic modulus efficiency was significantly higher than the tensile strength efficiency. This would suggest that sample failure was occurring through a mechanism other than pure tension.

If it is assumed that the reduction in modulus efficiency was due entirely to fibre damage, then by multiplying the theoretical composite tensile strengths by the modulus efficiency factors, corrected composite strengths are obtained which take this fibre damage into account.

The experimental results can then be compared with these 'corrected' theoretical strengths to give amended efficiency factors. These will represent the proportion of the composite tensile strength which was achieved before failure occurred through another mechanism.

The amended tensile strength efficiency factors are given in Table 7.5.

Several alternative mechanisms could be responsible for causing premature composite failure. These include delamination, stress concentrations, sample defects and test induced effects.

The possibility of delamination occurring between the prepreg and the matrix has already been discussed, stress concentrations could occur for several reasons, but perhaps the most likely are uneven distribution of the fibre reinforcement and end effects around the test rig jaws.

Sample defects causing failure could be damage caused through careless handling or, as frequently observed during the test programme, curvature.

Category	Series No.	V_f	Tensile Strength. (N/mm^2)	$Q_E \sigma_f V_f$ (N/mm^2)	Amended Efficiency Factor.
a)	T.1	0.049	34.0	-	-
	T.2	0.045	39.0	110.9	0.35
	T.4	0.043	41.0	85.5	0.49
b)	T.3	0.045	61.0	104.4	0.58
	T.5	0.047	68.3	125.4	0.54
	T.6	0.047	68.6	126.8	0.54
	T.7	0.047	56.3	90.0	0.63
	T.8	0.043	71.0	112.2	0.63
	T.9	0.040	67.5	112.5	0.60
c)	T.11	0.095	129.2	264.5	0.49
	T.12	0.091	137.0	250.7	0.55
	T.14	0.080	103.4	218.1	0.47

Where Q_E = Modulus efficiency factor.

TABLE 7.5 Amended Tensile Strength Efficiency Factors.

Test induced effects include such things as sample misalignment in the test machine and over-tightening in the test rig jaws.

Many of these potential causes of premature failure could be avoided through careful fabrication and testing. An even fibre distribution is perhaps not attainable as the prepreg format inherently concentrates the fibres. It could, however, be possible to obtain a more even distribution of the prepreg.

Most of these alternative failure mechanisms are particular to the fabrication and testing of small scale samples and would not apply to the full scale final format. The problem of delamination however is potentially the most serious as this is related to the material itself and not to its format.

7.7 Conclusions.

The ultimate tensile strength of the carbon fibre reinforced cement composite was less than expected for a material obeying the Rule of Mixtures.

The elastic modulus of the composite was generally much closer to the predicted values and suggested that the composite was obeying the Rule of Mixtures. The short fall in modulus efficiency could be accounted for by fibre damage.

Because of the discrepancy between the strength and modulus efficiency factors which were obtained in the test programme it seemed likely that sample failure was not entirely due to tensile failure of the fibre reinforcement but that some other factor was contributing to premature failure.

The most likely reason for premature failure was delamination between the prepreg and the matrix. It had been hoped to investigate this further through a study of the prepreg/cement bond but this proved impossible due to the shortage of available time.

CHAPTER EIGHT

Application of the Composite to Reinforce a Structural Element

8.1 Introduction.

In the research described in the previous chapters a carbon fibre reinforced cement composite material was developed which had useful stuctural properties.

This enabled the third stage of the research programme to be embarked upon. This section of the research examined, through a series of practical tests, the suitability and efficiency of this composite when used in the proposed application. That is of a system of combined permanent shuttering and tensile reinforcement for reinforced concrete structural elements.

8.2 Requirements.

For the composite to function successfully as tensile reinforcement certain values of tensile strength and modulus were required.

The results of the tensile tests on specimens of the composite sheet showed that the properties required had either been achieved or were potentially attainable.

The research programme concentrated on the structural properties of the composite which were required for reinforcement. However, if it is to function as a shuttering system in addition to providing reinforcement, several other factors need to be taken into account.

The composite sheet must be strong enough and rigid enough to support the wet concrete when it is poured. It must also be easy to handle and to use.

The rigidity of the composite is very important as it must not deflect unduly under the weight of the wet concrete. If additional propping is required because the sheet is too flexible, then the system may well become uneconomic.

The necessary stiffness could be achieved by using relatively thick composite sheets or by profiling the sheets, eg. by corrugation. This is potentially a more attractive solution and was considered in detail in Chapter 6.

Studies of the composite sheet and its properties in isolation do not reveal how well it will function when incorporated into a concrete structural element. If the element is to perform well, then the bond between the composite and the concrete is of critical importance.

A good bond is essential if stress transfer across the interface is to take place and concrete and composite are to act together as a structural element.

8.3 Practical Considerations.

For a system of shuttering to perform well, structural properties are not the only consideration.

Although no practical work was done, some thought was given to practical aspects of the potential use of the composite in sheet form.

Several factors were thought to be important and these are considered here.

a) Size.

The size of the composite sheets must not be so great that they become difficult to transport and to handle.

Size is especially important as the composite is acting as the tensile reinforcement as well as shuttering, it is unlikely that the composite sheets could be lapped or jointed in the same way that conventional reinforcement can be and therefore the length of span which is possible is governed by the length of sheet available.

Because of the problems of manufacturing and transporting very long sheets, this consideration puts a practical limit on the size of span for which the system can be considered.

A further complication is introduced when two way spanning slabs are considered. In these cases, the sheet must be prefabricated to the size and shape of the required floor and then be transported and placed in one piece.

For this reason it is likely that the use of these sheets could be restricted to one-way spaning slabs where the required span would determine the length of the sheet. The width of the floor would determine the number of sheets of a standard width which would be required.

b) Handling.

For ease of use on site the composite sheet must be easy to shape and cut as required with tools readily available on a building site. Any requirement for the use of specialised tools would reduce its attractiveness and possibly restrict its use to skilled operatives.

Experience in the laboratory has shown that the material can be easily cut using an ordinary hacksaw. This suggests that the material could be easily cut and shaped with common tools.

Weight is another factor which must be considered. If the material is so heavy that it requires excessive manpower or items of plant to handle, it will not find ready acceptance in the construction industry.

If it is assumed that the density of the composite is approximately the same as concrete, then the weight of a 6mm thick sheet, 1 metre wide and 6 metres long would be approximately 80 kg. It should not prove difficult for two men to carry and place such a unit in position.

c) Toughness.

The term 'toughness' is used here to describe the material's resistance to damage.

The rigours of on-site handling are well known to anyone who has worked on, or visited a typical construction site.

If a material is to survive on site it must be capable of standing upto the rough treatment and many abuses it will be subjected to. It will be dropped, probably on a corner or edge, it will have heavy objects dropped onto it. It will be run over by men and machines and it will be misused in ways that could not possibly be anticipated by the designer.

Although no material could be expected to stand up to worst of these abuses, it must be tough enough to be able to resist the more common.

Experience of working with the composite suggested that it should prove to be reasonably resistant to many of the lesser abuses it could be expected to suffer.

From the examples listed here it can be seen that there are many considerations and requirements which have to be satisfied before a new material such as this will find acceptance in the construction industry.

It was not appropriate to consider all these fully here, and this research was therefore limited to a study of the structural aspects of the composite's performance as reinforcement.

8.4 Factors Affecting Composite Performance.

Carbon fibres are expensive and this factor has prevented their use in the construction industry. Their attraction lies in their high tensile strength and if the high initial cost of the materials is to be off-set, this must be fully utilised.

It must therefore be ensured that, in the proposed application as tensile reinforcement for concrete structural elements, the element does not fail before the full tensile strength of the fibres has been realised.

In the design of a flexural concrete element it is generally assumed that the concrete has no tensile resistance of its own and that any tensile stresses must be resisted by reinforcement. The tensile stresses are transferred into the reinforcement across the interface bond.

If the interface bond between the concrete and the reinforcement breaks down before the carbon fibres have been stressed to their maximum capacity then the reinforcement will not be used economically.

The preliminary flexural test carried out on a beam in Chapter 6 indicated that interface bond failure and consequent delamination of the composite plate from the concrete was indeed a possible mode of failure and must therefore be considered.

The nature of this interface bond will determine its strength.

It is considered unlikely that any significant degree of chemical bonding will develop across the interface, though it is possible that if some of the cement in the composite sheet is not completely hydrated, some further hydration and crystal growth across the interface could take place.

Any bonding which does occur is more likely to be of a mechanical or frictional nature. The strength of this type of bond will depend largely upon the surface characteristics of the composite sheet. A rough or irregular surface will provide a good mechanical key allowing efficient stress transfer across the interface.

Delamination due to horizontal shear stress could occur not just at the interface, but also within the composite sheet itself. The interlamina shear strength of the composite must therefore be high enough to prevent this happening before the tensile strength of the fibres has been realised.

The flexural tests carried out on samples of composite sheet indicated that the interlamina shear strength of the composite was quite high and that this should not be a problem.

8.5 Structural Element Test Programme.

To study the structural performance of the composite sheets as reinforcement for concrete elements a number of flexural tests were carried out on reinforced concrete beams.

It was envisaged that the carbon fibre cement composite sheets could eventually be used as reinforcement for a variety of structural forms, from simple flat slabs spanning in one direction only, to beams and columns.

For these latter formats the composite material could be formed into troughs and tubes which would contain the wet concrete and would also act as reinforcement when the concrete was hardened.

Within the limited time available for practical research it was not possible to study thoroughly all the potential formats and uses for this new material.

The research carried out was therefore limited to the use of flat composite sheets containing unidirectional, aligned, carbon fibres. This form of the composite could be used to reinforce concrete floor slabs spanning in one direction only.

The behaviour of the composite in this format was studied through flexural tests carried out on beam elements which were used as a means of modelling simple slab behaviour.

8.6 Sample Format.

The preliminary flexural test on a relatively large beam element had demonstrated that tests on such a scale were impractical for several reasons.

A large beam element requires a correspondingly large composite sheet as reinforcement. The amount of prepreg required to fabricate such a sheet involved a considerable number of man hours in the preimpregnation process alone and the quantity of carbon fibre used was quite large.

The handling of such a large beam element proved quite cumbersome and transporting it to the test laboratory, which was some distance away, was an additional problem.

The only test machine which was available and capable of handling beams of this physical size had a maximum load capacity of 100 Tons. Consequently, in testing this element the machine was working very much at the lower end of its range where it was least sensitive. The accuracy of the recorded loads could not therefore be relied upon.

Because of the problems which had been experienced, it was decided to carry out tests on much smaller elements. This decision made fabrication, handling, and testing much easier.

Three sample formats were used and these were designated 'S, M and L'. The dimensions of each format were :

S Series	300 x 50 x 50 mm
M Series	500 x 100 x 100 mm
L Series	1400 x 100 x 100 mm

It can be seen that the 'S Series' samples were laboratory scale, the 'M Series' were somewhat larger, but were still small scale, and the 'L Series' were large enough to represent a typical lintol or short beam.

8.7 Structural Analysis of a Concrete Beam Reinforced with a Carbon Fibre Reinforced Cement Composite.

In order to understand the flexural behaviour of the concrete structural elements under test, a theoretical model was required from which could be derived the material stresses.

The idealised beam section which was used for this analysis is illustrated in Fig. 8.1.

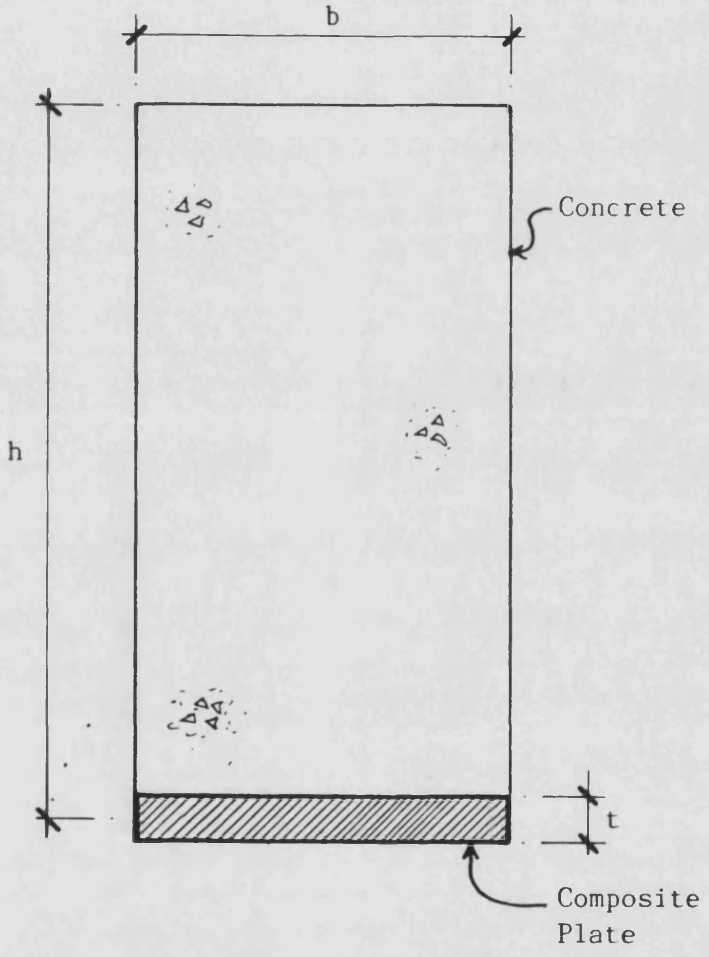


FIG. 8.1 The Idealised Reinforced Beam Section.

A number of assumptions were required, namely :

1) That the elastic modulus of the concrete in tension was the same as it was in compression.

2) That the concrete and the composite were intimately bonded together so that the strain in the composite and concrete at the interface were equal.

The beam analysis was carried out for two conditions.

a) At low loads, before tensile failure of the concrete.

b) After tensile failure of the concrete, ie. when all tensile resistance was provided by the composite.

8.8 Beam Behaviour at Low Loads.

The bending of the reinforced beam was considered on the basis of transformed sections, so that, the area of the composite plate (A) was replaced by an equivalent concrete area mA, where 'm' was the modular ratio, ie. $m = E_{composite}/E_{concrete}$.

The equivalent 'transformed' beam section was therefore of the form illustrated in Fig 8.2.

The neutral axis occured at the centre of area of the transformed section, such that, taking area moments about A-A :

$$n = \frac{b/2\,(h - t/2)^2 + mAh}{b(h - t/2) + mA} \qquad (8.1)$$

The Second Moment of Area for the transformed section was therefore given by :

$$I = \frac{bd^3}{12} + bd(d/2 - n)^2 + \frac{mAt^2}{12} + mA(h - n)^2 \qquad (8.2)$$

From the standard equations of bending, the stress in the section at any point a distance 'y' from the neutral axis was given by the expression :

$$\sigma = \frac{M\,y}{I} \qquad (8.3)$$

From this it can be seen that the tensile stress in the concrete at the interface is given by:

$$\sigma_i = \frac{M\,(h - n - t/2)}{I} \qquad (8.4)$$

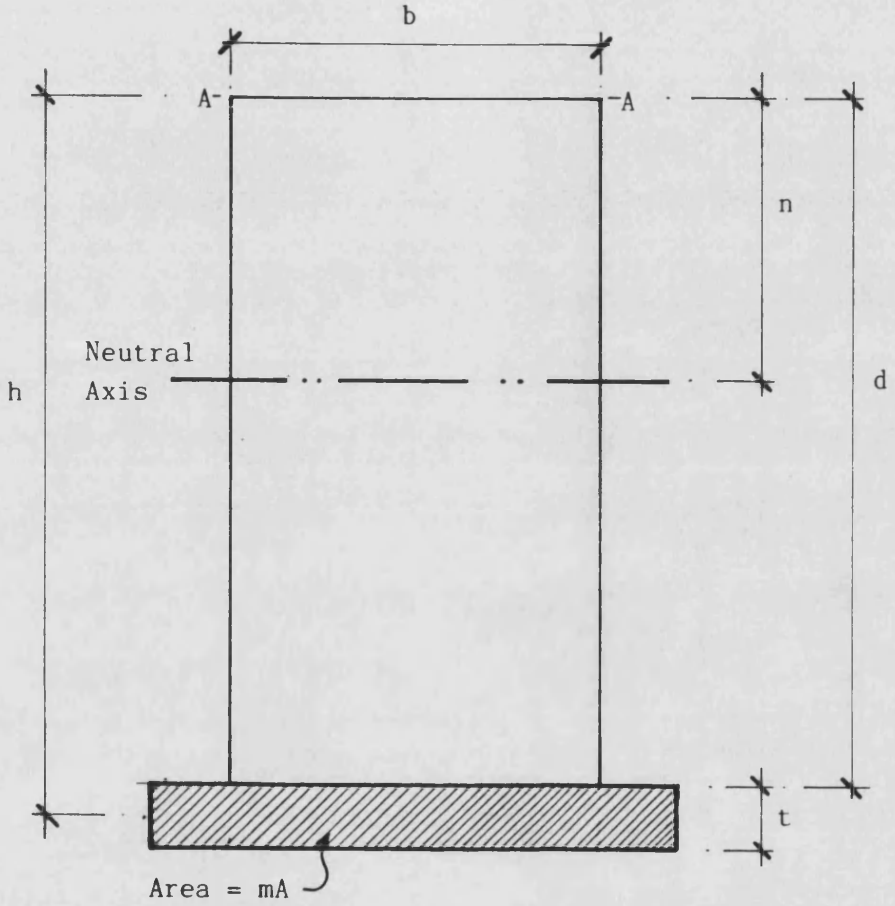


FIG. 8.2 The Transformed Beam Section.

The mean tensile stress in the composite plate σ_1 was therefore :

$$\sigma_1 = \frac{M(h - n)\, m}{I} \qquad (8.5)$$

The maximum tensile stress in the composite occurs at the bottom edge and is given by the expression :

$$\sigma_{1u} = \frac{M(h - n + t/2)}{I} \qquad (8.6)$$

The bond between the composite and the concrete at the interface had to be strong enough to transfer the tensile stress into the reinforcement. It can be shown that the interfacial shear stress between the two materials is given by the expression :

$$v_h = \frac{\sigma_1 (t)}{L/2} \qquad (8.7)$$

(Where L = span).

8.9 Beam Behaviour After Tensile Failure of the Concrete.

The beam was considered after the concrete had cracked in tension. In this case, the area of concrete below the neutral axis was considered to have no tensile resistance and was therefore ignored.

The transformed beam section for this case is illustrated in Fig 8.3.

As before, the neutral axis occurs at the centroid of the transformed section, and by taking area moments, the following expression for 'n' is derived :

$$n = \frac{mA}{b}\left(1 + \frac{2bh}{mA} - 1\right) \qquad (8.8)$$

The second moment of area of the transformed section is therefore given by :

$$I = \frac{bn^3}{3} + \frac{mAt^2}{12} + mA(h - n)^2 \qquad (8.9)$$

Hence the tensile stress in the composite plate can be derived from the standard equation of bending :

$$\sigma = \frac{My}{I}$$

Where y = the distance from the neutral axis and I is obtained from the equation above.

The mean tensile stress in the composite plate is therefore given by the expression :

$$\sigma_1 = \frac{mM(h - n)}{I} \qquad (8.10)$$

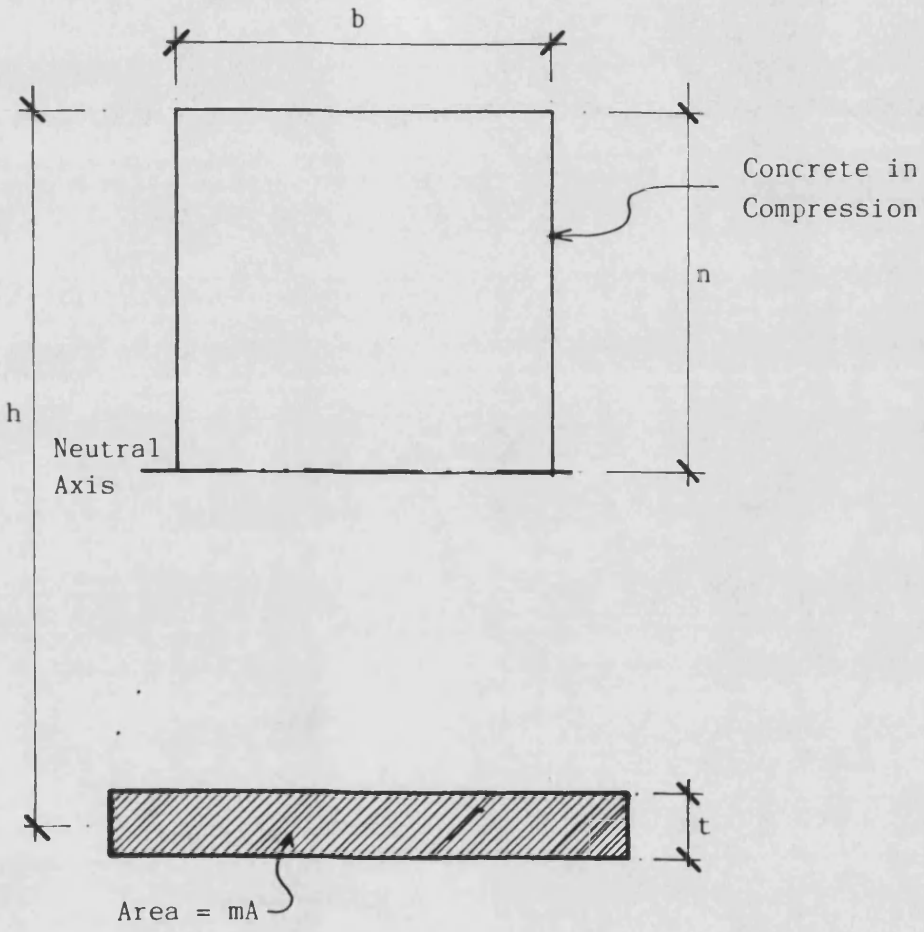


FIG. 8.3 Transformed Beam Section After Concrete Tensile Failure.

Similarly, the equation for the maximum tensile stress in the composite, at the outer edge, can be obtained by substituting for the distance from the neutral axis, such that :

$$\sigma_{1u} = \frac{mM(h + t/2 - n)}{I} \qquad (8.11)$$

8.10 Conclusions.

From the equations derived for the two cases it was possible to determine the stress distribution in the beam section for any applied moment 'M'.

The stress distribution for the ultimate case at failure of the beam could therefore be obtained by substituting for the maximum applied moment derived from the flexural tests.

This analysis of the composite section is stated in general terms and could be applied to any beam section reinforced by means of a plate on the underside.

8.11 'S' Series.

Two series of flexural tests were carried out on laboratory scale beam elements. These were numbered S.1 and S.2 .

The purpose of the S.1 series of tests was twofold, the initial consideration was simply to determine whether it was feasible to study beam behaviour at such a small scale, the second consideration was to study the strength of the bond between the composite and the concrete.

For the second series of tests the elastic modulus of the composite reinforcement was increased by increasing the fibre volume fraction. The purpose behind this was to determine whether a higher composite modulus would result in an earlier and more gradual transfer of tensile stress to the reinforcement. It was thought that this may reduce the likelihood of delamination.

8.11.1 Sample Preparation.

a) S.1 Series.

Five carbon fibre reinforced cement plates were made up in perspex moulds using the standard fabrication techniques described in Chapter 6.

The plates measured 300 x 50 x 3 mm, fourteen tows of prepreg were included in each to give a target fibre volume fraction of 0.04. PVA resin was added to the cement paste to give a resin/water/cement ratio of 0.1/0.35/1.0.

The plates were cured in their moulds in damp conditions for seven days. Twenty four hours before use they were demoulded and transferred to storage under water.

The beam elements were cast in plywood moulds which measured 300 x 50 x 50 mm.

The composite plates were taken directly from the curing tank and placed in the bottom of the moulds. A cement grout, water/cement ratio 0.5, was applied to the top surface. The concrete was then placed in thin layers, each layer was well tamped using a metal rod before the next was applied.

The tops of the beams were trowelled smooth and the samples were then stored in damp conditions, under wet sacking, for 72 hours before being demoulded and transferred to a curing tank.

The samples were removed from the curing tank 24 hours prior to testing.

Two 100mm concrete cubes were cast using the same mix as that used for the beams and these were tested at the same time as the beam samples.

The samples were tested at beam age 14 days, (plate age 22 days).

b) S.2 Series.

Six composite plates were made up in two piece perspex moulds using the same techniques as the S.1 Series.

Thirty five tows of prepreg were included in each plate to give a target fibre volume fraction of 0.10. The resin/water/cement ratio of the cement paste was amended to 0.13/0.45/1.0 to increase its workability.

The cement plates were stored in their moulds in damp conditions until twenty four hours before use. The plates were then demoulded and stored in damp conditions until required.

The damp plates were placed in the bottom of the plywood beam moulds which measured 300 x 50 x 50 mm and the concrete was placed in thin layers. Each layer of concrete was well tamped before the next was applied.

The top of each beam was trowelled smooth, and after an initial 72 hours in damp conditions the beams were demoulded and transferred to a curing tank. The beams remained in the curing tank until 4 days prior to testing.

Three 100mm cubes were cast using the same concrete as used for the beams and these were tested at the same time as the beam samples.

The samples were tested at beam age 17 days, (plate age 31 days).

8.11.2 Test Format.

The beam elements were tested in three-point bending using an 'Instron 1122' test machine with a maximum load cell capacity of 500 kg.

The rate of loading was controlled by the speed of cross-head displacement, for the S.1 Series this was set at 0.2 mm/min and for the S.2 Series it was set at 0.5 mm/min.

The first sample of the S.1 Series was initially tested over a span of 200 mm, however it was found that over this span the sample was capable of sustaining the full load capacity of the test rig without visible signs of distress.

In an attempt to induce sample failure within the capacity of the test rig the span was subsequently increased to 250 mm and the sample was retested. The span of 250 mm was then adopted for the remaining samples in both test series.

A graph of load vs. cross head displacement was automatically recorded by the test machine.

The concrete cubes were tested in compression using an 'Avery Denison' cube crushing machine.

8.11.3 Results.

a) S.1 Series.

Of the five samples tested in the S.1 Series, only one failed within the 500kg capacity of the test machine. The remaining samples in the series all sustained this maximum load without failing.

In the sample where failure occurred, S1.02, this was by delamination of the composite plate from the underside of the concrete.

Examination of the remaining samples after testing revealed no evidence of distress.

Examination of the load vs cross-head displacement graphs plotted automatically by the test rig revealed that all the samples exhibited very similar behaviour.

A typical example of this is illustrated in Fig. 8.4.

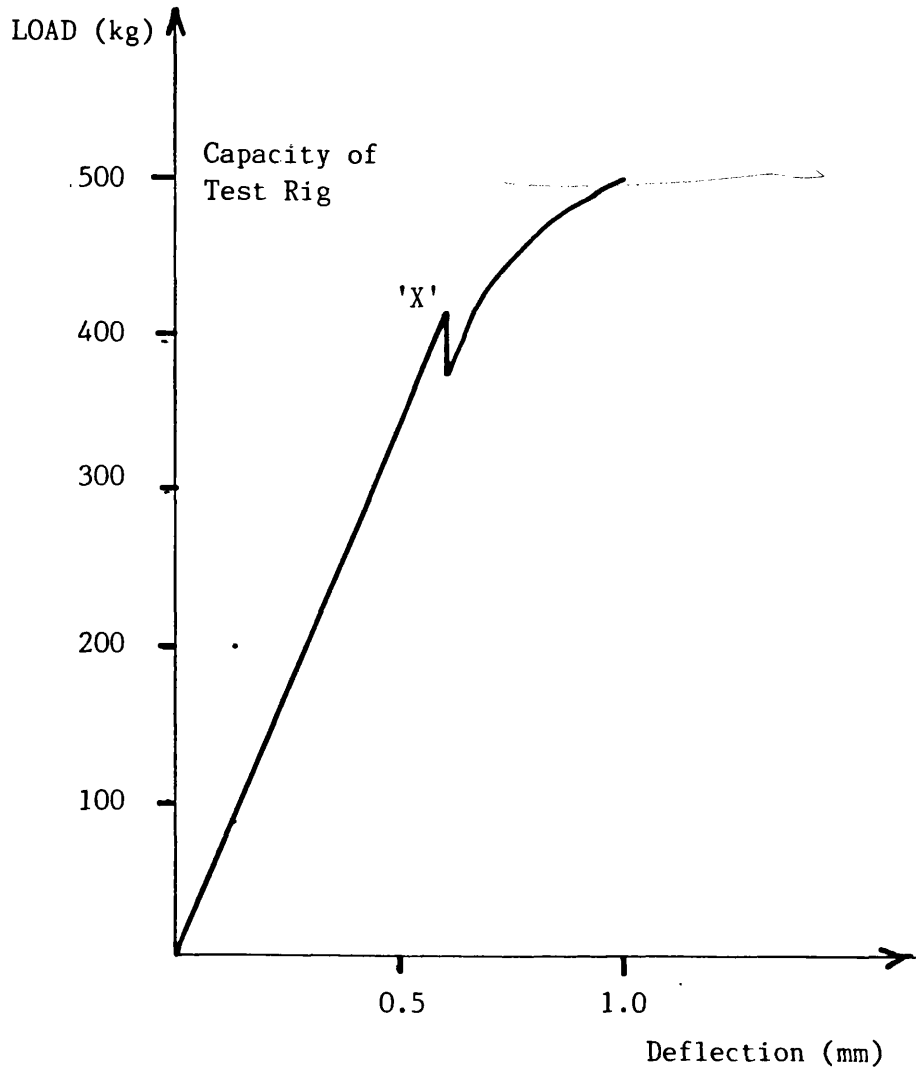


FIG. 8.4 S.1 Series Flexural Behaviour.

In all cases there was a definite point (ref. 'x' in Fig. 8.4) where there was a sudden change in composite performance. Prior to this point, the initial part of the graph was fairly steep and linear, whereas the second portion of the graph was less steep and curved.

The loads at which this feature occurred are recorded in Table 8.1.

Two possible reasons for the presence of this feature were considered. It was felt that either it could represent the point at which the concrete failed in tension and the tensile stress was then transferred to the composite plate, or it could mark the beginning of delamination of the composite plate.

The stress distribution in the beam was analysed using the method of transformed sections described earlier, with particular reference to the point at which this feature occurred.

For the purpose of the analysis it was first assumed that this point in the graphs represented the point of tensile failure of the concrete. Two stress distributions were derived for this point, the first representing the condition if the concrete had not cracked and the second if it had. (ie. 'Pre' and 'Post' tensile failure of the concrete).

A further analysis considered the stress distribution under the maximum load sustained.

The results of these analyses are recorded in Table 8.2.

The compressive strength of the concrete was derived from the results of compressive tests as 47.0 N/mm^2

Sample	Load (N)	Deflection (mm).
S1.01	4145	0.65
.02	3738	0.42
.03	4218	0.69
.04	4336	0.99
.05	4101	0.61
MEAN	**4108**	**0.67**

TABLE 8.1. S.1 Series : Recorded Loads at Point 'X'.

Sample No,	Moment Nmm	Composite Stress N/mm²		Interfacial Shear Stress	
		Pre.	Post	Pre.	Post
S1.01	259063	6.32	33.85	0.16	0.88
.02	233625	6.21	33.00	0.15	0.81
.03	263625	6.35	34.71	0.16	0.91
.04	271000	6.95	37.64	0.17	0.94
.05	256313	6.33	33.57	0.17	0.89
MEAN	**256750**	**6.43**	**34.55**	**0.16**	**0.87**

a) Stress Distribution at Point 'X', 'Pre' and 'Post' Concrete Tensile Failure.

Sample No,	Moment Nmm	Composite Stress N/mm²		Interfacial Shear Stress	
		Pre.	Post	Pre.	Post
S1.01	306563		40.1		1.04
.02	285103		40.3		0.99
.03	306563		40.4		1.05
.04	306563		42.6		1.06
.05	306563		40.2		1.07

b) Stress Distribution at Maximum Load.

TABLE 8.2 S.1 Series. Analysis of Stress Distributions.

b) S.2 Series.

All of the samples in the S.2 Series failed within the capacity of the test machine, the mean failure load was of the order of 415 kg. In all cases failure occurred by delamination of the composite plate from the underside of the concrete section.

The graphs of sample behaviour under test for these samples showed linear behaviour until sudden and catastrophic failure, except in one or two cases, where sample failure occurred in a series of partial failures, indicated by steps in the load/deflection graphs.

Typical graphs of the two failure types are illustrated in Fig. 8.5.

It can be seen from these graphs that there was no change in composite behaviour as had been observed in the S.1 Series. However it was noted that the loads at which sample failure occurred were very similar in magnitude to the loads at which the change in gradient had occurred in the S.1 Series.

This suggested that either tensile failure of the concrete was occurring simultaneously with total sample failure, or that for some reason delamination in the second series was sudden and total.

It was decided to analyse the beam stress distribution at failure load for both the condition where the concrete had not failed and for when it had. The results of this analysis are recorded in Table 8.3.

The compressive strength of the concrete, obtained from the results of crushing three 100 mm cubes, was 51.5 N/mm^2

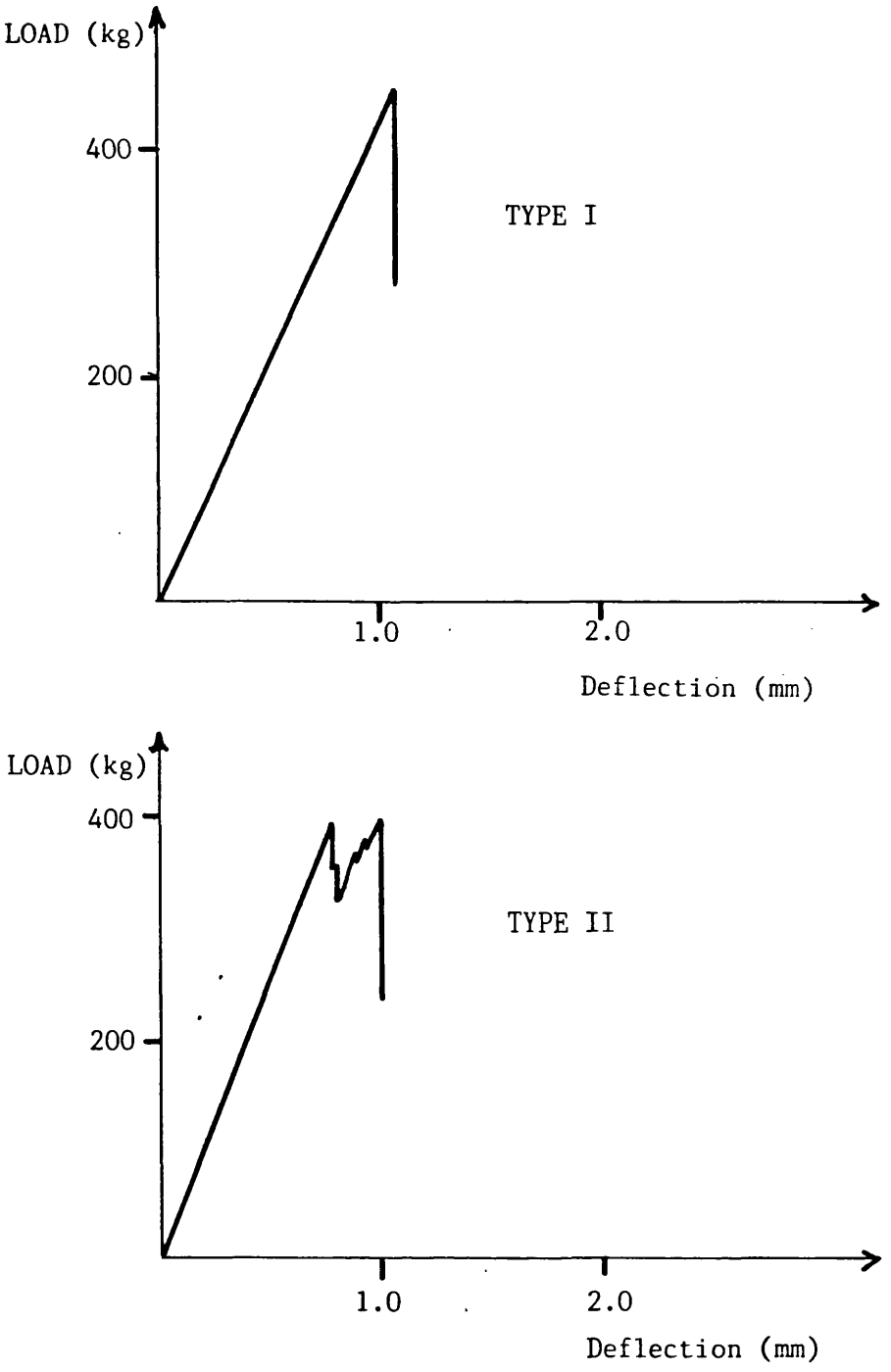


FIG. 8.5 S.2 Series Flexural Behaviour.

8.11.4 Discussion of Results.

It had been expected that the higher plate modulus of the second group of samples, by virtue of their higher fibre volume fraction, would result in improved structural properties. However this does not appear to have occurred in practice.

The analysis of the feature which occurred in the S.1 Series tended to indicate that this was not the point at which tensile failure of the concrete was occuring.

From Table 8.2 it can be seen that the mean composite stress at this point, derived from the pre-cracking model was 6.43 N/mm^2, the modular ratio was determined to be 0.53. These figures would suggest a tensile stress in the concrete at that point of about 12.0 N/mm^2.

This is far higher than the expected tensile strength of the concrete which is commonly assumed to be approximately 10% of the compressive strength, this would give a value not greater than 5.0 N/mm^2.

The analysis of the S.1 Series stress distribution under the maximum applied load derived a value of approximately 40 N/mm^2 for the tensile stress in the composite plate.

The results of the tensile tests in previous chapters would suggest that such a plate, having a fibre volume fraction of 0.038 would have a tensile strength efficiency factor of about 0.59 (T.9 Series).

The theoretical tensile strength of the composite would therefore be given by the expression :

$$\sigma_{tu} = 0.59\ (\sigma_{fu} V_f)$$

$$\sigma_{tu} = 0.59\ (2900 \times 0.038) = 65\ N/mm^2$$

It can be seen therefore, that at the maximum loads sustained the composite plate was working at approximately 60.0% of its theoretical tensile capacity.

Why the second series of tests failed at lower applied loads than the first series was not immediately obvious. It could have been expected that the higher modulus and tensile strength of the composite in the second group would have resulted in better performance, but this does not appear to be the case.

Analysis of the results of the S.2 Series showed that the composite tensile stresses at failure were generally lower than those sustained by the S.1 Series without failure. Though the interfacial shear stresses were slightly higher. The results are recorded in Table 8.3.

It was possible that slightly different fabrication techniques led to a reduced interfacial bond strength in the second series. The composite plates used as reinforcement for the S.1 Series had been very wet when they were placed in the bottom of the beam moulds and prior to placing the concrete the top surface of the plate had been brushed with a cement grout.

The plates used for the S.2 Series were only damp, not wet, when used and no grout was applied.

Ultimate Condition :

Sample No.	Moment Nmm	Composite Stress.		Interfacial Shear Stress.	
		Pre.	Post.	Pre.	Post.
S2.01	223800	12.2	33.3	0.31	0.84
.02	282100	14.8	38.6	0.39	1.02
.03	245300	13.3	34.2	0.35	0.90
.04	252600	12.4	32.2	0.36	0.93
.05	303500	14.4	38.5	0.40	1.07
.06	220800	11.3	29.2	0.30	0.79
MEAN	254683	13.1	34.3	0.35	0.93

TABLE 8.3 S.2 Series. Analysis of Stress Distributions, 'Pre' and 'Post' Concrete Tensile Failure.

It was also noted that the age of the S.1 Series plates when incorporated into the beams was 8 days, the age of the S.2 Series samples was 14 days.

It was thought possible that the measures taken with the S.1 Series may have produced a better bond between the composite and the concrete and that this had led to the higher strengths.

Comparison of the interfacial shear stresses (post cracking) which correspond to the change in composite behaviour in the S.1 Series with the interfacial shear stresses at failure of the S.2 Series show them to be very similar (approx. 0.9 N/mm^2).

8.11.5 Conclusions.

The results of the 'S' Series of tests on laboratory scale samples rather contradicted expectations.

The S.2 Series had been expected to perform better than the S.1 Series as a result of its improved composite properties, in fact it failed at lower loads.

The analysis of the S.1 results showed that the change in profile of the load/deflection graphs was unlikely to represent the point at which tensile failure of the concrete was occuring.

It was possible however that this in fact marked the beginning of delamination of the composite from the concrete. Because the bond strength in the S.1 series had possibly been improved by the fabrication methods, delamination would not occur as quickly and the samples continued to take load. In the S.2 Series, however, when delamination did occur it was sudden and catastrophic.

These tests served to prove that the interface bond between the composite and the concrete was of utmost importance and that the behaviour of the structural element was likely to be governed by the performance of this bond.

8.12 'M' Series.

Flexural tests were carried out on two groups of samples.

The samples used in this test series were larger than those used in the previous test series and it was hoped that the results obtained would be more representative of full scale beam behaviour than was the case when very small samples were used.

The M.1 Series of tests was used as a 'control' group and consisted of unreinforced concrete prisms which were used to determine the flexural properties of the concrete itself.

The M.2 Series was used to study the behaviour of the beams in flexure when reinforced with a composite plate on their underside and to determine the mode of failure.

8.12.1 Sample Preparation.

The composite plates used as reinforcement for the M.2 Series were manufactured in 'two piece' perspex moulds and had smooth surfaces, top and bottom.

The basic fabrication techniques were the same as used in the production of previous tensile samples. The target fibre volume fraction was 0.10 and seventy tows of prepreg were included in each of the composite plates which measured 600 x 100 x 3 mm.

In order to facilitate the inclusion of the relatively high fibre volume fraction a resin/water/cement ratio of 0.13/0.45/1.0 was used.

After fabrication the plates were demoulded and were stored under water in a curing tank for approximately ten days until required.

The composite plates were removed from the curing tank and were placed in the bottom of steel moulds prior to the placing of the concrete. The plates were in a wet condition, but no surface water was present.

The beam moulds measured 500 x 100 x 100 mm and the concrete was placed in three layers, each being well vibrated before the next was poured.

The concrete prisms of the M.1 Series were cast in identical steel beam moulds using similar techniques.

The same concrete mix was used for both the reinforced and the unreinforced beam elements and the ratio of constituents was water/cement/sand/gravel : 1.5/3.0/5.1/9.0 .

The beams were cured in identical conditions under water in a curing tank until 48 hrs before testing, they were then removed from the tank and allowed to dry.

Both test series were tested at age 28 days.

8.12.2 Test Format.

The samples were tested in bending using an 'Avery' transverse testing machine. A span of 406 mm was used and equal point loads were applied at third points.

The rate of loading was controlled by the speed at which the cross beam was raised relative to the fixed loading points. A constant rate of loading of 0.625 Tons/min was selected for both groups.

The load was applied in stages of 0.5 Tons (Total Load) for the M.1 Series and 0.25 Tons for the M.2 Series. At each load stage the deflection of the test samples was measured indirectly using dial gauges which recorded the relative displacement of the supports at each of the fixed load points.

8.12.3 Results.

a) M.1 Series.

The unreinforced concrete prisms all failed as expected, by tensile failure of the concrete. This was evidenced by cracks which started on the bottom face below one of the load points and which then spread rapidly upwards through the section until total failure took place with the beam element seperating into two parts.

A full analysis of the results of these tests was carried out using the standard equations of bending. This indicated that the tensile stress in the concrete at failure was of the order of 4.9 N/mm^2.

A summary of the results is recorded in Table 8.4.

The elastic modulus of the concrete was derived from analysis of the deflection under load using the 'moment Area' method. A mean value of 10700 N/mm^2 was obtained. The values of deflection recorded at each load stage are given in Table 8.5.

The characteristic compressive strength of the concrete of 40 N/mm^2 was obtained from tests carried out on cubes made from the same mix.

It is generally assumed that the tensile strength of concrete is approximately 10% of the value of the compressive strength and it can be seen from these results that this assumption was broadly correct.

b) M.2 Series.

All of the reinforced samples failed by delamination of the composite plate from the concrete.

The delamination was generally initiated beneath a load point and then spread along the beam towards the support until total failure occurred.

Sample No.	Load (N)	Moment (Nmm)	Section Modulus (mm^3)	Failure Stress. (N/mm^2)
M1.01	6603	893606	175138	5.10
M1.02	6230	843127	175570	4.80
M1.03	6230	843127	175568	4.80
M1.04	6230	843127	175134	4.81
M1.05	6853	927439	176868	5.24
M1.06	6230	843127	175435	4.78
			MEAN.	**4.92**

TABLE 8.4 M.1 Series : Summary of Results.

Sample No.	Load. (N)	d_1	d_2	d_{mean} (mm)
M1.01	1246	0.05	0.05	0.05
	2492	0.11	0.07	0.09
	3738	0.13	0.09	0.11
	4984	0.16	0.12	0.14
	6230	0.19	0.16	0.17
	6603	F A I L U R E .		
M1.02	1246	0.11	0.06	0.08
	2492	0.17	0.07	0.12
	3738	0.21	0.09	0.15
	4984	0.21	0.11	0.16
	6230	F A I L U R E .		
M1.03	1246	0.06	0.00	0.03
	2492	0.10	0.04	0.07
	3738	0.13	0.08	0.10
	4984	0.15	0.10	0.13
	6230	F A I L U R E .		
M1.04	1246	0.04	0.02	0.03
	2492	0.07	0.05	0.06
	3738	0.09	0.08	0.08
	4984	0.11	0.10	0.10
	6230	F A I L U R E .		
M1.05	1246	0.04	0.03	0.04
	2492	0.07	0.05	0.06
	3738	0.08	0.08	0.08
	4984	0.10	0.10	0.10
	6230	0.12	0.12	0.12
	6853	F A I L U R E.		
M1.06	1246	0.03	0.04	0.04
	2492	0.08	0.07	0.08
	3738	0.11	0.09	0.10
	4984	0.15	0.11	0.13
	6230	F A I L U R E .		

TABLE 8.5 **M.1 Series Loads and Deflections.**

Graphs of applied load vs. deflection for each of the M.2 Series samples are shown in Fig. 8.6. These had two distinct portions of different gradient. The first section, in the load range 0.5 - 2.0 Tons was linear and of fairly steep gradient, the second section was also linear but of much less steep gradient.

It can be seen from the graphs that the results were fairly consistent and that the plots for each sample were fairly tightly grouped.

It was assumed that beam failure took place in three stages :

1) Tensile failure of the concrete.

2) Massive increase in interface stress.

3) Failure of bond and delamination of the plate.

These two sections of the graphs would therefore appear to represent the beam behaviour before and after the concrete had failed in tension.

The change in gradient of the load vs deflection graphs occurred in the load range 2.0 - 2.5 Tons (ie ≈ 20000 - 25000 N).

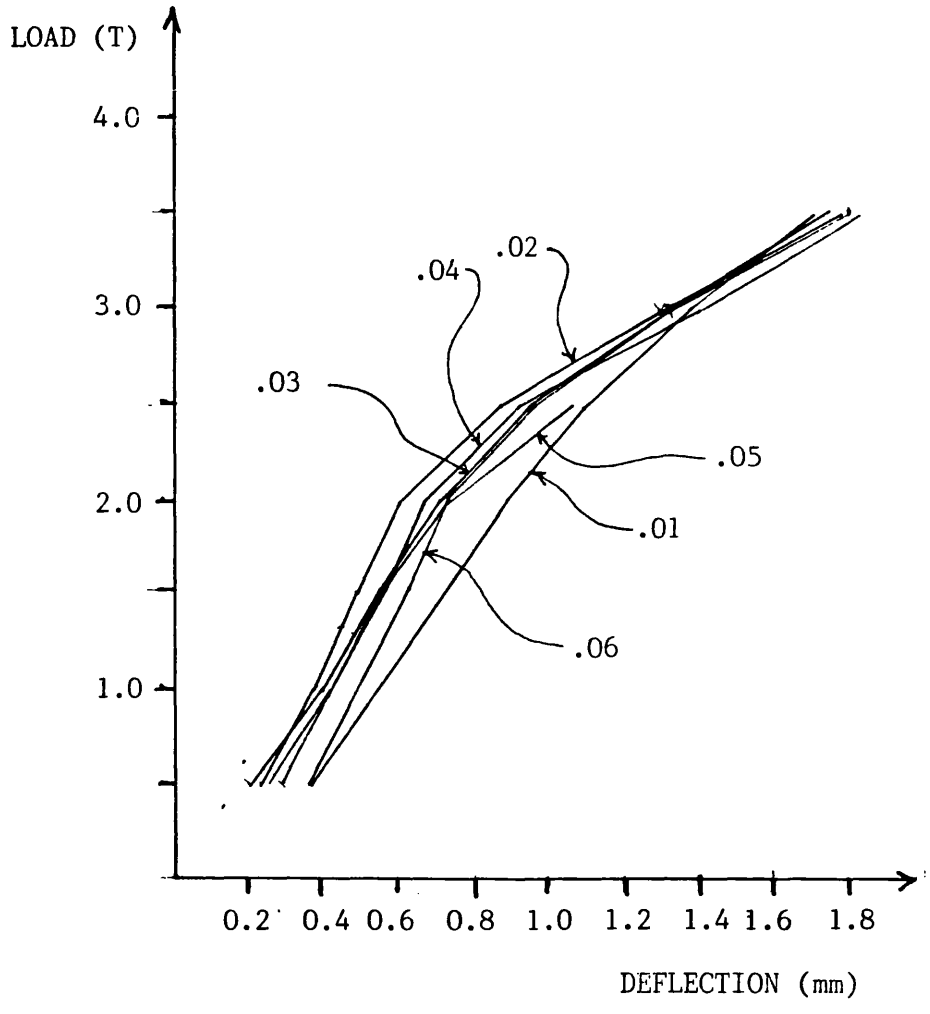


FIG. 8.6 M.2 Series : Load/Deflection Curves.

A mean value for the load at this point of 22500 N was assumed, using the analysis derived previously and substituting for the value of elastic modulus derived for the concrete in the M.1 Series, the following mean stress values were obtained :

Tensile stress, concrete	7.30 N/mm^2
Tensile stress, composite	11.70 N/mm^2
Stress at Interface	0.37 N/mm^2

These values applied if it was assumed that the concrete had not yet cracked. The beam was then analysed at the same load, but in this case it was assumed that the concrete had cracked in tension, the following mean results were obtained :

Tensile stress, composite	41.90 N/mm^2
Stress at Interface	1.33 N/mm^2

The beam samples did not fail completely at this load, but delamination of the plates then continued gradually until total failure took place.

By analysis of the beam at failure, the following mean ultimate stess values were obtained :

Tensile stress, Composite	66.47 N/mm^2
Stress at Interface	2.11 N/mm^2

From an examination of the samples after testing, it was noted that although initially the delamination seemed to take place at the interface, as the delamination spread, the failure surface entered into the depth of the composite plate itself.

8.12.4 Conclusions.

These two series of tests showed that the strength of concrete beams reinforced with a carbon fibre reinforced cement composite plate was governed more by the interfacial shear strength of the interface bond and the interlaminar shear strength of the composite itself than by the tensile strength of the composite.

The mean ultimate tensile stress generated in the composite before failure was of the order of 66.0 N/mm^2. This compared with a predicted composite tensile strength of approximately 108 N/mm^2 (based on V_f = 0.075, and a tensile strength efficiency of 0.5).

Analysis of the beam sections at the possible concrete cracking load of 22,500 N indicated that at this load value the tensile stress generated in the uncracked concrete was almost certainly high enough to induce tensile failure if this had not already occurred.

As was also seen in the 'S' Series of tests, the composite material appeared to be only utilising approximately 60% of its ultimate tensile strength before the beam elements failed by delamination.

The group of tests on the control samples produced a set of basic properties for unreinforced concrete which could then be used as the basis for further analysis of the behaviour of reinforced sections.

8.13 Derivation of Theoretical Interfacial Shear Strength.

The programme of flexural tests carried out on concrete beam elements reinforced with CFRC plates on their underside had indicated that the dominant failure mode was delamination of the composite plate from the concrete.

The delamination, in all cases, took place before the full theoretical tensile strength of the composite had been realised.

Premature failure of the beams by delamination inferred that the carbon fibre reinforcement was not being used economically. Because of the high material cost of carbon fibres, it was extremely important that their full potential was utilised.

The strength of the interface between the composite and the concrete is dependant upon several factors, it is unlikely that there will be any significant chemical bond between the two materials and therefore the most important component of the bond will be frictional. It is possible that if the cement matrix of the composite is not fully hydrated some further crystal growth may take place across the interface and this may add to the strength of the bond.

The strength of the interface between precast and insitu concrete has been studied by a working group of the FIP Commission on Prefabrication and they have produced a 'Guide to Good Practice'[46] which gives recommendations on the design strength of the interface and on the factors which may affect this.

The guide classifies the surface type of the precast element and describes ten types which range from a smooth surface as obtained by casting the unit against a steel or timber shutter to a surface which has been provided with mechanical shear connectors.

The composites which have been used in this research were formed in perspex moulds which resulted in very smooth, almost shiny, surfaces.

As well as considering the surface roughness of the precast element the guide also considers surface treatments, factors such as cleanliness, compaction, curing and wetting of the surface have a major influence on the shear strength of the interface.

Before the insitu concrete is placed the surface of the precast element should be inspected with regard to laitance and for the presence of contaminants which may inhibit bond. The surface can be cleaned by water flushing, compressed air, or vacuum cleaning. Brushing the surface to remove contaminants is not recommended as this merely sweeps any dust into the small depressions of the interface.

In order to reduce differential shrinkage between the precast and insitu components water treatment is recommended. However before use, any surface water must be removed as the presence of water hinders the penetration of micro depressions in the surface by the cement paste. A wet interface can result in a reduction in bond strength of upto 50% compared to a dry interface.

If it is correctly executed, the surface of the composite could be prepared by the use of a cement grout. This must be applied sufficiently close to the pouring of the concrete to prevent the grout from drying. A badly applied grout, which is allowed to partly dry would result in a possible reduction of the interface strength.

The FIP guide gives a method for deriving the theoretical shear strength of an interface, this is based on the results of experiments carried out on many composite beams and slabs. The equations for the design shear strength of the interface include a factor of 0.7 (to take account of the statistical variation of the experimental results) and a safety factor of 0.5 (to allow for the difference between quality control in the laboratory and in practice).

The design shear strength of the interface is defined as :

$$v_{hu} = \beta_2 \sigma_{td}$$

where *for smooth surfaces,* $\beta_2 = 0.1$

σ_{td} = *design tensile strength of concrete* = $0.25\sqrt{f_{cu}}$

$$\therefore v_{hu} = 0.1\ (0.25\sqrt{f_{cu}}\ )$$

The ultimate shear strength can therefore be derived by removing the safety factors such that :

$$v_{hu} = \frac{0.1(0.25\sqrt{f_{cu}})}{0.7(0.5)}$$

$$v_{hu} = 0.0714\ (\sqrt{f_{cu}})$$

This formula was used to derive the theoretical interface shear strength for the Test Series S.1, S.2 and M.2. The results of this analysis are given in Table 8.6 .

Test Series	f_{cu} N/mm^2	v_{hu} N/mm^2
S.1	47.0	0.49
S.2	51.5	0.51
M.2	54.0	0.52

TABLE 8.6 Theoretical Interface Shear Strengths (V_{hu}).

It will be recalled from the results of these test series, that the stress at the interface was obtained in each case for the point at which it was believed that delamination could have begun. Two values of stress were obtained, for the concrete in the cracked and uncracked condition.

These values are summarised in Table 8.7.

It can be seen from Table 8.7, that in all cases the interface stress for the pre-cracking condition was less than the theoretical interface strength, but that in the post cracking condition there was a massive increase in stress to a level well above the theoretical strength.

These results suggested that tensile cracking of the concrete may have resulted in the interface being over stressed. This would have led to failure of the interface bond and delamination of the composite.

8.14 Conclusions.

The FIP Guide to Good Practice suggests that the strength of the interface between a precast composite plate with a smooth surface and insitu concrete is of the order of 0.5 N/mm^2.

Analysis of the results of the beam tests carried out indicated that sample failure by delamination of the composite plate was likely to occur and that this may have been initiated by tensile failure of the concrete.

Test Series	v_h (uncracked)	v_h (cracked)	v_{hu}
S.1	0.16	0.87	0.49
S.2	0.35	0.93	0.51
M.2	0.37	1.33	0.52

TABLE 8.7 Mean Interface Shear Stresses.

8.15 'L' Series.

This was the first (and last) extensive set of tests on composite reinforced beam elements of a size which could be called 'full scale'. It was thought that the results of this series of tests would be of greater significance than those tests caried out on smaller, laboratory scale samples.

The series of tests was carried out over a period of almost three months, as the Test Series progressed certain significant factors came to light and these were taken into account in the later tests.

Unfortunately because of time constraints it was not possible to do any further testing and this resulted in it being impossible to follow up some of the ideas that emerged as a result of the test programme.

The series was limited to ten samples and was therefore not as statistically significant as one would have liked, however it did serve to act as a pointer towards areas of research and development which may prove fruitful in the future.

8.15.1 Sample Format.

The composite plates used for all the samples were cast in two piece perspex moulds using the standard hand lay-up techniques described elsewhere. Seventy individual tows of prepreg reinforcement were included in each sample to give a target fibre volume fraction of 0.10. In practice the mean fibre volume fraction of the composite plates was of the order of 0.07 (7.0%).

The plates were approximately 100mm wide and 3mm thick.

The cement paste was made up using PVA resin in the proportions resin/water/cement : 0.13/0.45/1.0.

After fabrication the composite plates were stored in their moulds and were cured in damp conditions until required.

When used, the composite plates were in a damp condition, there was no surface water present and no cement grout was applied to the top surface.

The beam samples were cast in timber moulds which measured 1500 x 100 x 100 mm. The composite plates were placed in the bottom of the moulds and then the concrete was placed in a minimum of three layers, each layer was well vibrated before the next was applied.

The beams were stored in their moulds, and were maintained in damp conditions, by storage under wet sacking, until they were tested.

It was found that this size of beam was very convenient as it could be handled by one person without undue difficulty, the approximate weight of each beam sample was 40 kg.

8.15.2 Test Format.

The beam elements were tested in three point bending over a span of 1219mm, (48") using an 'Avery Denison' test machine, this is illustrated in Fig. 8.7.

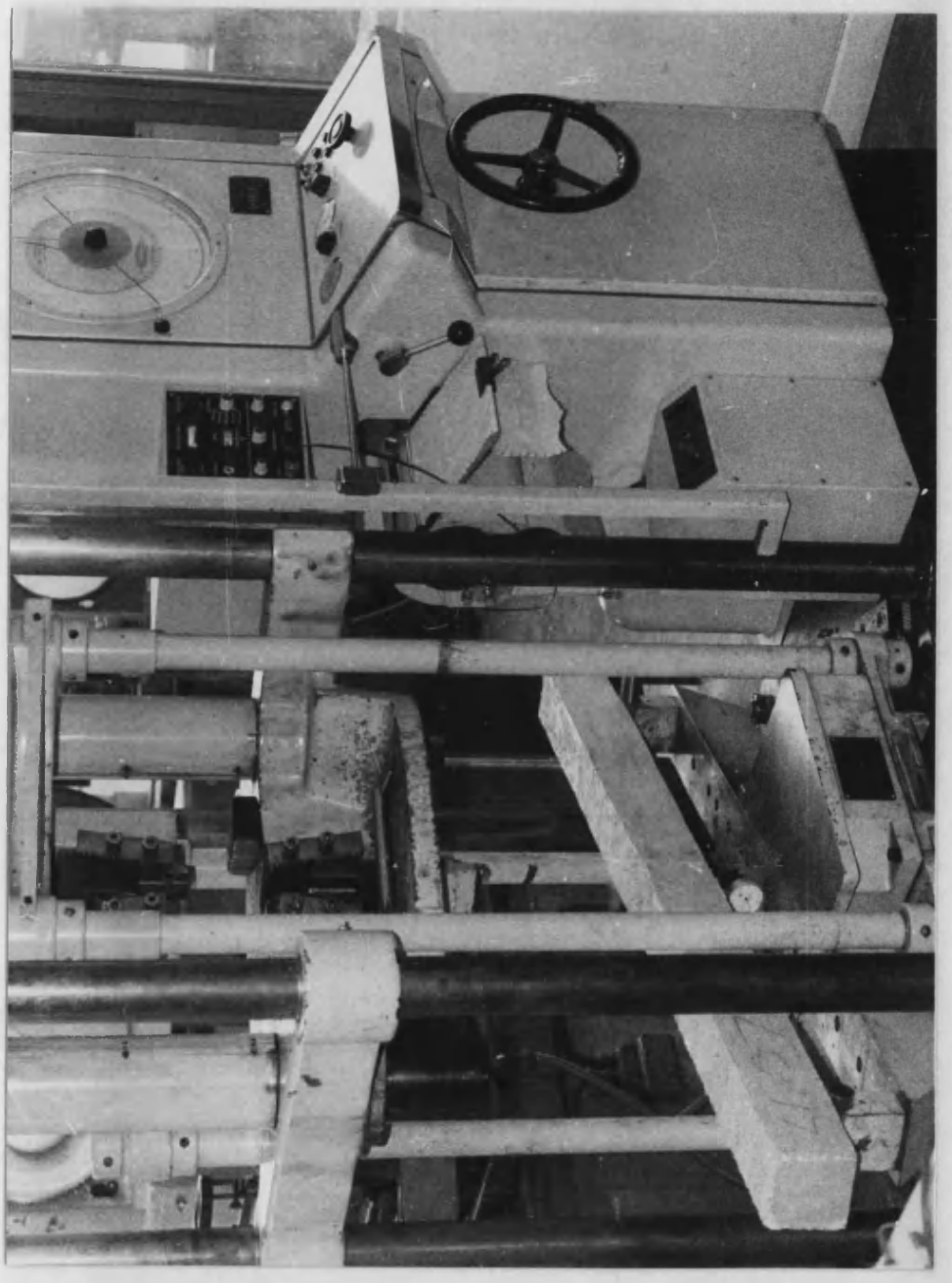


FIG. 8.7 'L' Series Test Arrangement.

The central point load was applied in increments of 1.0 KN upto a load of 5.0 KN, it was then increased in 0.5 KN stages until 6.0 KN. At each increment of load the deflection of the beam at mid-span was measured using a dial guage.

Beyond 6.0 KN, or as failure approached, the dial guages were removed for safety, and the applied load was then increased until sample failure occurred.

8.15.3 Results.

All of the ten samples in this test series failed by delamination of the composite plate from the underside of the concrete section.

The delamination was generally preceeded by a tension crack appearing in the concrete section, just above the composite plate in the centre region. The delamination then spread laterally from this point along the concrete/composite interface towards one end. Eventually one half of the beam became totally delaminated and failure took place.

Graphs of load vs deflection were plotted for each sample and these are shown in Fig. 8.8.

The load/deflection curves for the samples under test were very tightly grouped, this suggested very similar beam behaviour in each case.

It can be seen from Fig. 8.8 that the behaviour of the beams had two distinct stages, this was shown by the change in gradient as the applied load was increased.

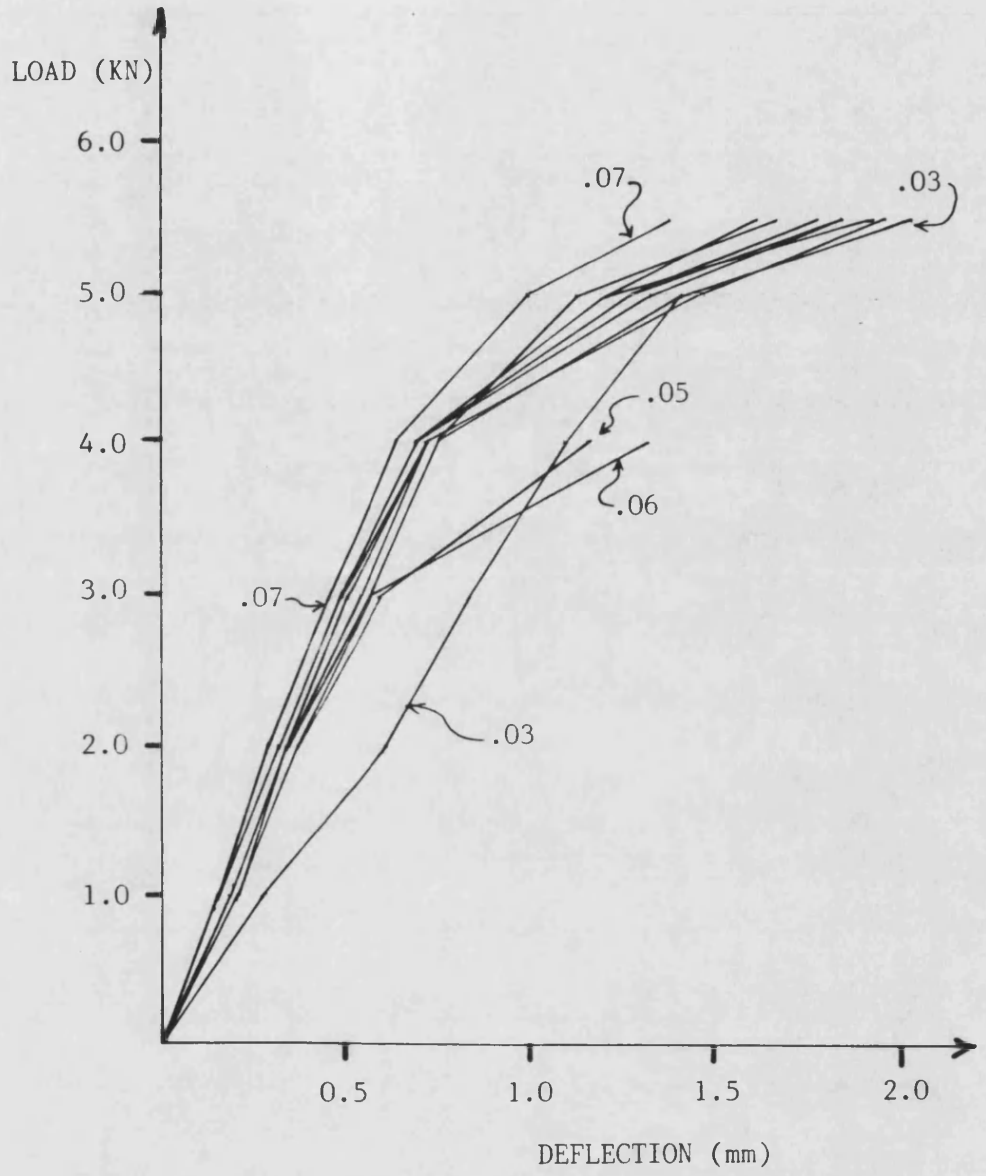


FIG. 8.8 'L' Series : Load vs. Deflection.

The first section of the graphs, over the load range 0.0 - 4.0 KN appeared to be linear, beyond 4.0 KN the graphs became much less steep and curved towards the horizontal, ie the rate of increase in deflection, in the later stages, was greater than the rate of increase in load.

In the case of two of the samples, L1.05 & .06 the graphs of load vs. deflection were linear only until a load of 3.0 KN, thereafter becoming much less steep.

It seemed reasonable to assume that the beams were behaving in a similar manner to the smaller scale laboratory samples of earlier test series and that the change in gradient of the load/deflection graphs represented the point at which the concrete failed in tension and delamination of the composite plate commenced.

The rapidly decreasing gradients of the later stages of the load/deflection graphs represented the increasing deflection under almost constant load as the composite plates delaminated from the concrete.

8.15.4 Analysis of Results.

In order to carry out an analysis of the results of the L Series it was assumed that for samples L1.05 & .06 tensile failure of the concrete/delamination of the composite occurred at a load of 3.0 KN and that for the remaining samples it occurred at a load of 4.0 KN.

The results were then analysed in the same way as the previous Test Series for the three conditions :

a) Concrete uncracked

b) Concrete cracked.

c) Ultimate.

The properties of the plain concrete were assumed to be the same as those derived in the M.1 'control' series of tests. (ie. concrete elastic modulus = 10700 N/mm^2).

The results of the analysis are summarized in Table 8.8(a).

Cube tests were carried out on samples of the concrete mix used for construction of the beam elements and these were found to have a mean compressive strength of 45.0 N/mm^2

The mean tensile stress in the concrete for conditions (a) and (b) was derived as 5.79 N/mm^2

As the tensile strength of concrete is commonly assumed to be approximately 10 % of its compressive strength it would appear reasonable to assume that at the load considered the concrete was close to, or had exceeded, the limit of its tensile strength.

The beam samples were then analysed in the ultimate condition, ie at failure, from this, an indication of the amount by which the tensile strength of the carbon fibre had been mobilised could be derived.

The stress distributions in the ultimate condition are summarized in Table 8.8(b).

Sample No.	Moment (Nmm)	Interface Stress Pre.	Post	Composite Stress. Pre.	Post.
L1.01	1219000	0.31	1.10	8.59	30.6
.02	1219000	0.30	1.10	9.60	34.6
.03	1219000	0.31	1.12	9.16	32.8
.04	1219000	0.31	1.11	9.11	32.7
.05	914000	0.23	0.83	6.19	22.1
.06	914000	0.23	0.84	5.90	21.5
.07	1219000	0.29	1.05	8.73	31.3
.08	1219000	0.31	1.10	9.43	34.0
.09	1219000	0.30	1.10	9.07	32.7
.10	1219000	0.29	1.09	8.75	33.3

TABLE 8.8(a) Stress Distribution at 3.0/4.0 KN.

Sample No.	Moment (Nmm)	Interface Stress (N/mm^2)	Composite Stress. (N/mm^2)
L1.01	2688000	2.42	67.5
.02	3017000	2.72	85.7
.03	3002000	2.77	80.7
.04	2048000	1.86	54.9
.05	1798000	1.64	43.4
.06	2267000	2.08	53.3
.07	3169000	2.73	81.5
.08	2743000	2.48	76.4
.09	3139000	2.83	84.3
.10	3005000	2.68	82.1
MEAN	2688000	2.42	71.0

TABLE 8.8(b) Stress Distribution : Ultimate Condition.

The theoretical tensile strength of such a composite, derived from the Rule of Mixtures and based upon a fibre volume fraction of 0.07 was given by :

$\sigma_{1u} = 0.07\ (2900)\ 0.5$

where 0.5 = typical tensile strength efficiency factor.

$\therefore \sigma_{1u} = 101.5\ N/mm^2$.

It can be seen that at failure, the stress generated in the composite was within the range 43 → 84% of the expected tensile strength.

8.15.5 Discussion of Results.

It was noted that three of the beam elements, samples L1.04, L1.05 & L1.06 failed at much lower loads than the earlier samples L1.01 - L1.03.

The reasons for this were not immediately apparent as at first sight the samples seemed to be almost identical, the method of composite manufacture in each case had been the same and the beams were of similar age when tested.

Careful examination of the samples where failure had occurred at lower loads, after testing revealed very little evidence of any bonding between composite and concrete and the failure surface corresponded almost exactly with the surface of the composite.

Examination of the earlier samples, which had failed at higher loads, revealed that parts of the composite surface had remained bonded to the concrete and had pulled away from the main body of the composite at failure. This indicated that quite a good bond had been achieved.

In discussing the likely bond between composite and concrete earlier, the possibility of crystal growth across the interface was considered, for this to occur the cement in the composite must be incompletely hydrated.

It was at this point that the age of the cement matrix of the composite at the time of casting the concrete for the beam was considered. In the case of the first three samples the plate age ranged from 12 to 14 days. In the case of the three weaker samples, the age range was from 18 to 26 days.

It appeared therefore that the age of the plates at the time of casting the beam concrete may be important and that the older plates had bonded less well.

Two of the later samples in the series, L1.09 & L1.10, were cast with much younger plates (5 & 10 days respectively) to determine whether this did improve performance. The results of these two samples showed an increase in the ultimate strength of the beams of over 50 % compared with those samples where the plates had been much older. These results therefore appeared to confirm this hypothesis.

As the early results had shown the importance of the interface bond between composite and concrete, the possibility of improving the mechanical performance of this bond by introducing a textured surface to the composite was considered.

The texture was introduced by sandwiching a layer of 'air bubble' plastic packing material beneath the lid of the mould forming the composite plate. This produced a surface texture consisting of circular indentations, approximately 5mm in diameter and approximately 1 mm deep. The indentations were spaced at about 15 mm centres.

Unfortunately it was only possible to introduce this technique for one of the samples, L1.09, and although this sample did appear to perform better than most, it was not possible to state categorically that the improvement was entirely due to the textured surface.

If time had permitted it was intended to study the effects of textured surfaces in further tests. It was thought that this was an area which would merit further work, a more extensive study of the effect of plate age upon the strength of the interface bond also appeared to be justified.

8.15.6 Conclusions.

It seems quite clear that the critical factor in the use of carbon fibre reinforced cement as reinforcement for concrete is not the tensile strength of the composite, but the strength of the interface bond between the two materials.

Nevertheless, the loads sustained at failure by the samples under test were quite reasonable and would certainly compare favourably with the loads a traditional lintel would be expected to carry.

CHAPTER NINE

A Summary of the Research

9.1 Introduction.

The programme of research described in this thesis consisted of two distinct phases, the first objective was the production of a carbon fibre reinforced cement composite and in the second phase the use of this material to provide the tensile reinforcement for concrete structural elements was considered.

As each phase of the research programme progressed the aims and objectives were amended to take into account the developments which arose.

For example, in the first phase the original concept of using fibre tows which had been spread to allow matrix penetration was abandoned in favour of the use of preimpregnated fibres. This was due to the difficulties of pre-spreading the fibres.

Similarly in the second phase it was soon realised that the critical factor which governed the strength of the reinforced elements was not the tensile strength of the composite, but the shear strength of the bond at the interface between the composite and the concrete.

9.2 The Composite Material.

The objective of the first phase of the research was to produce a composite material which consisted of a cement matrix reinforced with continuous, unidirectional carbon fibres.

This was achieved, and the composite material which resulted had quite useful structural properties.

Initially it had been intended to use untreated tows of carbon fibre (containing upto 12,000 individual fibres). These would be pre-spread to allow the cement matrix to come into contact with every fibre and also to achieve an even distribution of fibres throughout the composite.

The search for an efficient method of pre-spreading the fibre tows began with the use of water flumes. These were very successful at achieving an even distribution of fibres, but the method had intrinsic problems as, when spreading was completed, the fibres needed to be dried before they could be used.

Many methods of drying the fibres were explored, but all proved extremely slow or impossible to use in a continuous process on a laboratory scale.

It is possible however, that on a commercial scale, a method of fibre drying which retains the spread format of the fibres could be developed.

The difficulties encountered with the 'wet' spreading processes led to the development of a dry spreading method. This eased the fibre tows apart by using gentle currents of air. This method proved quite successful and combined with the use of a water soluble fixative to hold the spread fibres in place, it was possible to produce continuous tows of spread fibres with very good fibre distribution.

Tensile tests were carried out on samples of cement composite reinforced with these dry spread fibres and these indicated that quite good composite properties were attainable using this method.

If time had allowed it could have been worthwhile to have developed the spread-fibre concept further and to determine through a more extensive programme of tests whether in the long term this fibre format could have performed as well as that eventually chosen.

In an ideal situation, both the spread fibre format, and the prepreg method of composite production could have been developed simultaneously, as both showed promise, however, in the real world it was only possible to develop one of the methods and the dry-spreading approach was reluctantly dropped in favour of the prepreg approach.

The use of carbon fibres which had been preimpregnated (prepregged) with a resin matrix was first considered when the problems of the wet-spreading approach were being experienced.

A study of the available prepreg systems revealed that the most widely used resin was epoxy. It was thought that this might not be particulary suitable for use in cement composites. Epoxy resin prepregs were also very expensive and it was thought that the cost of such a system would prevent it finding a commercial application.

Prepregs did however seem to have potential as the prepregged fibre tows were easy to handle and seemed less prone to damage than the spread fibres. An alternative resin system was therefore sought.

This led to the consideration of Polyvinyl Acetate (PVA) resin, this seemed to offer a possible solution as it was water soluble and therefore it was thought that this would be more compatible with the cement paste.

It is believed that this is the first time that carbon fibres preimpregnated with PVA resin have been used to produce a cement composite.

The function of the resin was to impregnate the fibre tows and bond intimately with every fibre. Because PVA was water soluble it was possible to obtain a bond with the cement matrix without the need for the cement particles to penetrate the fibre tows.

As carbon fibres which had been preimpregnated with PVA were not commercially available it was necessary to develop a method of producing the prepreg in the laboratory.

Several methods were tried and refined and a system was developed which produced preimpregnated tows of carbon fibre in convenient 2.0 metre lengths.

Methods of manufacturing a cement composite using prepregged fibres were explored and after several refinements a process was developed which resulted in a product of reasonably consistent properties. In fact the system was still extremely crude in some aspects, particulary the application of the cement paste, but the properties of the resulting composites were quite reasonable.

The use of perspex moulds, and in particular the introduction of a lid to produce a smooth upper surface and to apply pressure during curing seemed to improve the properties of the resulting composite.

But perhaps the biggest breakthrough in the manufacture of the composite was the addition of PVA resin to the cement paste. This resulted in a significant improvement in the composite properties and almost eliminated any tendancy for the composite to delaminate under tensile load.

At the end of this first phase of the research programme a carbon fibre reinforced cement composite was being produced which had quite consistent and predictable properties and which, it had been shown, followed the Rule of Mixtures.

The objective of the first phase of the research programme had been achieved. The methods by which this had been brought about were not those originally envisaged and the process had taken more time than was intended, but that is the nature of research.

9.3 The Composite Reinforced Structural Element.

The objective of the second phase of the research was to develop a method of reinforcing concrete structural elements using the composite material which had been produced in the first phase.

The second phase was unfortunately curtailed by the limit of time available. This meant that it was not possible to fully explore all the avenues of research which presented themselves.

Nevertheless, useful results were obtained, and possible directions for future research were indicated.

Several series of flexural tests were carried out on concrete structural elements reinforced with CFRC plates on their underside. The results of this test programme quite clearly showed that the most important factor in the reinforcement process was not the strength of the composite plate itself, but the strength of the interface bond between the composite and the concrete.

Of all the beams which were tested, where failure occurred it was by a break down of this bond and delamination of the composite from the bottom of the beam. Analysis showed that failure by delamination was occuring when the stresses induced were below the theoretical tensile strength of the composite plates.

Despite this premature failure the larger structural elements did resist quite substantial loads before failure and this indicated that there was some potential for this format.

The second phase of the research, because of the limited time available, raised more questions than it was possible to answer.

Results indicated that there appeared to be a significant relationship between the age of the composite plate when the concrete for the beam was poured and the strength of the interface bond.

There also appeared to be a possiblity of improving the mechanical performance of the interface by the introduction of a textured composite surface.

It was also planned to investigate other methods of improving the interface bond, perhaps by the use of PVA resin as a bonding agent.

The possible elimination of the interface bond problem by combining the manufacture of the composite and the beam into a continuous process was also on the agenda of proposed research.

It is not claimed that the second phase of the research was complete and exhaustive, it would be fairer to say that it represented the first exploratory steps into a much larger field.

However the results which were obtained could prove extremely useful in acting as signposts for the future and for those that follow on the same path.

The objectives of the second phase had been achieved in part, in that concrete structural elements reinforced using the CFRC composite had been produced and these had carried significant loads before failing. The next phase would be to eliminate premature failure of the beams by delamination so that the full tensile strength of the composite reinforcement could be utilised.

9.4 The Future ?.

The programme of research described in this thesis demonstrated that it was possible to produce a carbon fibre reinforced cement composite which had useful structural properties. It also showed that by careful control of the manufacturing process it was possible to accurately predict the composite properties in advance.

The later stages of the research began the search for the most economic and appropriate end use for this material.

It had been originally envisaged that this would be in the form of flat sheets serving as combined permanent formwork and tensile reinforcement for reinforced concrete structural elements. However, it would appear from the results of the the research that this may not be the most economic use of the material as the structural elements which were tested failed before the full strength of the reinforcement had been realised.

Possible alternative uses for the material were therefore considered.

Carbon fibres are high performance fibres with very high strength to weight ratios. If they are to be used economically, full use must be made of their excellent structural properties and in particular their high tensile strength.

Fibre reinforced cements have already found wide acceptance in the construction industry and some of the many applications have been described in an earlier chapter. GRC in particular has been used very successfully in the manufacture of cladding panels and other non-structural precast concrete units.

Carbon fibres are a very expensive material, consequently upto now they have been used mainly in operations where cost is a secondary consideration after weight (for example, the aircraft industry). In these operations, the structural advantages and low weight of carbon fibre composites have outweighed the disadvantage of their high initial cost.

The construction industry is highly competitive and although the weight of structural elements is important, the first consideration is, more often than not, cost.

This requirement demands that carbon fibres are used in truly structural applications rather than in the non-structural formats in which other fibre-cements have found applications.

One possible use of carbon fibre reinforced cement which was considered was in the construction of lightweight box-section structural members, these could, perhaps, be used as precast floor planks or lintels.

Another possibility was to use the material to form the hull of a boat, or canoe.

Unless full use can be made of the outstanding structural properties of the carbon fibres it is not thought that the use of CFRC in the construction industry could ever be economically viable.

If the composite is to be able to compete economically with traditional materials then the cost of production will be a critical factor. To this end, the amount of fibre damage which occurs during the manufacturing process will have to be kept to a minimum.

The end use must be one which does not allow premature failure of the structural element before the full tensile strength of the reinforcement has been realised.

Carbon fibre reinforced cement is a viable structural material which appears to have much potential. But if that potential is to be realised in the manner proposed the problem of interface bond will need to be overcome.

It is quite possible that a combination of the ideas suggested by the last series of flexural tests would eventually overcome this, only further research would show.

9.5 Conclusions.

It would appear that carbon fibre reinforced cement does have a future as a structural material, but the success of that future depends as much as anything on the economic viability. From the results of this research it seems likely that the proposed end use as tensile reinforcement may not be the most economic and that some other format will have to be developed.

It is hoped that the research described in this thesis may help some future research worker along the road towards realising the full potential of carbon fibre reinforced cement.

APPENDICES

APPENDIX ONE

The Relationship Between 'E', 'v', and 'G'

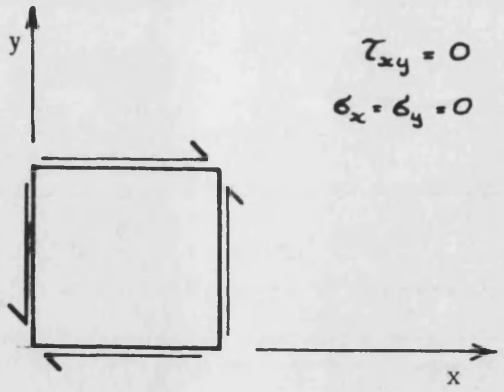
The shear modulus of a material 'G' is not independant of the elastic modulus of that material 'E' and its Poisson's ratio 'v'[27][28].

To determine the relationship between these constants consider a reference state of plane stress at a point, involving only a shear stress $\tau_{xy} = \tau_o$, ($\sigma_x = \sigma_y = 0$) (Fig A1.1(a)). The principal-stress element for this pure-shear reference is at 45° to the reference element, and the principal stresses are $\sigma_1 = +\tau_o$ and $\sigma_2 = -\tau_o$. This is illustrated in Fig A1.1(b).

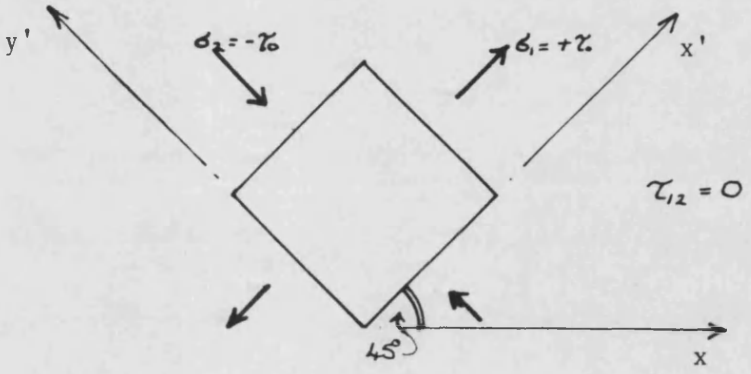
The strains for the reference element are $\gamma_{xy} = \gamma_o$ and $\epsilon_x = \epsilon_y = 0$. The normal strains for the principal element are $\epsilon_1 = +\gamma_o/2$ and $\epsilon_2 = -\gamma_o/2$. The shear strain for the principal element is given by $\gamma_{12} = 0$.

The deformed reference and principal-stress elements are shown superimposed in Fig. A1.1(c) to illustrate the relationship between the strains of these elements.

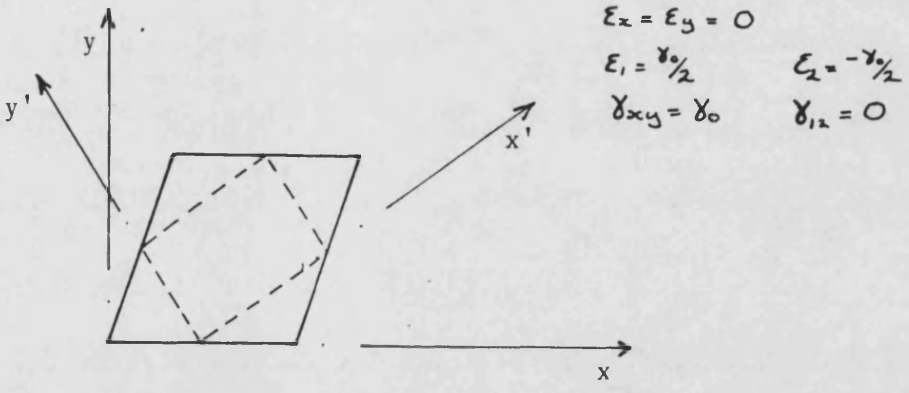
The relationship between the shear stress for the pure-shear reference element and the normal stresses for the principal normal-stress element requires that the stress/strain equations for the pure-shear and pure-normal-stress elements be related.



(a) Pure-Shear Reference Stresses.



(b) Principal Stress Element for Pure-Shear Reference Element.



(c) Strains for Reference and Principal Elements.

FIG. A1.1 Relationships Between Stress and Strain Components.

For the pure-shear reference element the shear strain is given by the relationship :

$$\gamma_o = \tau_o/G \qquad (A.01)$$

For the normal-stress principal element, the material strain is given by :

$$\epsilon_1 = \sigma_1/E - \nu\sigma_2/E \qquad (A.02)$$

Since $\epsilon_1 = \gamma_o/2$, this can be substituted into the relationship for shear strain, eq. (A.01), to give :

$$\epsilon_1 = \tau_o/2G \qquad (A.03)$$

The principal stresses $\sigma_1 = +\tau_o$ and $\sigma_2 = -\tau_o$. Therefore, if these are substituted into the equation for material strain, eq. (A.02) the expression becomes :

$$\epsilon_1 = (1 + \nu)\tau_o/E \qquad (A.04)$$

If these two expressions for the material strain are equated it can be seen that the relationship between that material constants is given by :

$$G = E/2(1 + \nu) \qquad (A.05)$$

APPENDIX TWO

The Manufacture of Cement

A2.1 The Wet Process.

The wet process is perhaps the oldest method of manufacturing cement, and it was the most widespread. However, since a great deal of heat is required to evaporate the water, the rapid increase in fuel costs over the last 10 - 15 years has made it less attractive.

An early description of the wet process was given by Pasley in 1828 after visiting the works belonging to James Frost and this is included here as Fig. A2.1.

The wet process is more commonly used with soft raw materials, such as chalk and clay. The basic item of plant in the production of slurry is the washmill. This is a circular basin with vertical sides and a central shaft carrying four radial arms. From the arms tined harrows are suspended by chains.

As the harrows are dragged round the mill by the rotating arms the soft raw materials are reduced to a fine particle size suspended in the water fed into the mill. Heavy particles such as gravels and flints settle to the bottom and are periodically removed.

As the materials are washed the liquid slurry flows off through gratings around the upper wall of the washmill and is screened or is passed through a hydrocyclone to separate any remaining oversized particles. The fine slurry then passes into storage tanks.

From the storage tanks the slurry is blended to control the final composition before being stored. Storage takes place in large concrete slurry tanks equipped with revolving arms which pump air into the slurry to keep it agitated, thoroughly mixed and in suspension for drawing off into the kiln.

The modern wet process is illustrated in Fig. A2.2 and it can be seen that it is remarkably similar to that described by Pasely in 1828.

All the water in the slurry must eventually be driven off by heat in the kiln. Therefore, the water content of the slurry is kept to the minimum required to maintain it in a fluid state. Reduction of water content makes an important contribution to manufacturing efficiency, especially when fuel costs are high. Chemical additives have been successfully introduced in the majority of wet process works to reduce slurry water content whilst maintaining workability.

Because of the amount of drying required, kilns for the wet process are proprtionately longer than those required for other processes.

From this point on the wet and dry processes are broadly similar.

Mr Frost used chalk ground in two mills, each having four iron wheels and two harrows with a sand trap or pit near it for getting rid of the sand. The fluid chalk ground in these mills and the clay - which was the fine brown pit clay from the neighbourhood of Upnor, were then mixed together in a washmill, precisely similar to that used by brickmakers. When sufficiently incorporated, the mixture was, by opening a small sluice, allowed to flow into a back or reservoir where it usually remained some months and aquired the consistency of a stiff paste. In this state the material was cut out of the back in lumps and laid on open shelves to dry. When dried the lumps were broken into smaller pieces and burnt in a kiln of the common inverted-cone like form and in the same manner as lime with alternate layers of fuel and cement. When sufficiently burnt, the calcined cement was ground by two pairs of the same sort of millstones used for corn, after which the powder was preserved in casks or sacks. The chalk wash and grinding mills were all worked by a steam engine said to possess thirty horse power.

FIG. A2.1 Description of the Wet Process, 1828.

A2.2 The Dry Process.

The dry process involves the milling and blending of raw materials in the dry state rather than in a slurry. The dry process is therefore best suited to raw materials having a low natural moisture content. Typically this process is used for the harder materials, ie. limestone and shale, but as the alternative wet process has become increasingly more expensive the dry process is now being used for the softer materials as well.

Primary crushing of the raw materials is carried out at the quarry where the stone is reduced to a managable size to enable it to be transported by conveyor belt.

After crushing the material is stockpiled prior to milling. The most common type of mill is the 'tube mill'. Frequently these mills are air swept so that the material is dried as well as ground.

When milling is completed the raw meal passes to the blending and storage silos. Here the products of several milling operations are blended to ensure a consistent mixture.

Before it enters the kiln the meal is often preheated by exhaust gases from the kiln itself.

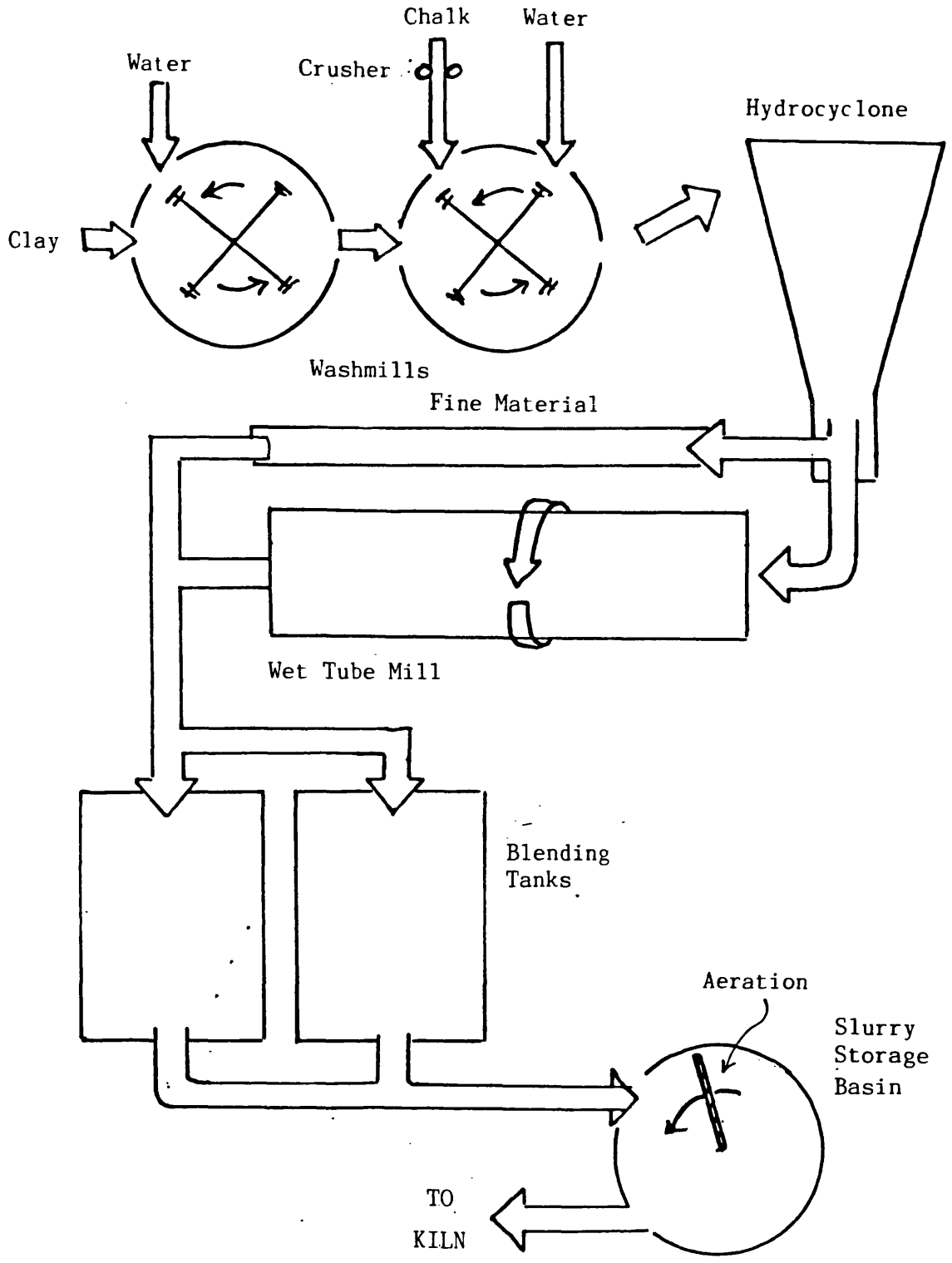


FIG. A2.2 **The Modern Wet Process.**

A2.3 The Semi - Dry Process.

The semi dry process is significantly different from the wet and dry processes prior to the firing stage.

At an early stage of this process the raw materials are formed into pellets or nodules containing a moderate ammount of moisture. The use of nodules allows very efficient pre-heating on an enclosed moving grate.

Energy consumption of the semi dry process is similar to that of the dry process and about half of the wet process. This process produces a clinker of a uniform size.

As in the dry process, the raw materials are first processed into a meal, water is then added to give a moisture content of around 12 - 14%.

The mix is then fed into the nodulizer, which is a rotating inclined dish. As the dish revolves the meal is formed into roughly spherical nodules. The size of which depends upon the installation, but is generally in the range of 10 - 40 mm.

From the nodulizer the nodules pass into a moving grate preheater known as a 'Lepol' grate. This is illustrated in Fig. A2.3. The preheater is divided into two compartments, the drier and the calciner. The nodules are fed onto the grate which carries them in turn through the drier and the calciner.

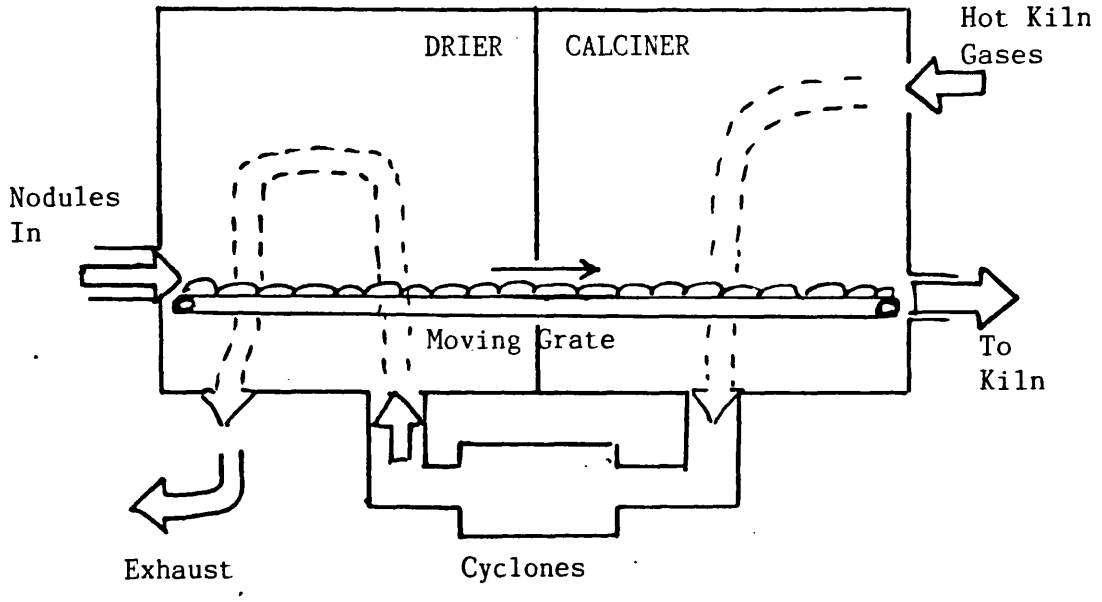


FIG. A2.3 **The 'Lepol' Grate Preheater.**

Exhaust gases from the kiln enter the grate chamber at temperatures in the range 870 to 1150°C and are drawn down through the grate bed in the calciner by a fan. Dust is removed at this stage by cyclones and the gases are then fed up through the grate bed in the drier compartment.

After passing through both calciner and drier compartments the temperature of the exhaust gases has dropped to around 115°C and they are then drawn through electrostatic precipitators to remove any remaining dust before finally being vented through the kiln stack.

The preheated and partly calcined nodules are then fed into the kiln for firing as in the wet and dry processes.

APPENDIX THREE

Polyvinyl Acetate Adhesive

Polyvinyl Acetate (PVA) is a polyvinyl ester adhesive and has many uses throughout industry. It is commonly available in three forms, solution, aqueous dispersion and for use by the hot-melt technique.

The aqueous dispersion form which was used in this research is manufactured by the industrial process of emulsion polymerisation. In this process the liquid monomer is first emulsified in water and is then polymerised by heating in the presence of a catalyst.

The product is not a true emulsion as it is not a liquid/liquid system but is an aqueous dispersion of swollen solid particles.

Polyvinyl Acetate adhesive is useful for a number of porous and fibrous materials such as paper, wood and leather, it can also be used for non porous materials such as transparent plastic films.

After PVA has been applied to an adherand, water is eliminated from the emulsion through evaporation and absorption by the adherand. This results in the swollen particles coalescing to form a coherent adhesive film.

In order to improve film formation a plasticiser is added and this has an unfortunate side affect which is the main disadvantage of PVA, that is creep under stress, especially at raised temperatures.

Creep can be reduced by modifying the PVA with the addition of a urea formaldehyde resin, but the effect of creep upon the long term stability of a composite containing PVA must be considered.

A recognised application of PVA emulsion is its use as a bonding agent to increase the adhesion between new and old concrete. This can be done in one of two ways, either by coating the old concrete with PVA before the new concrete is applied, or by including a proportion of PVA in the new mix.

PVA adhesives are non-toxic, clean and easy to use, and they gain strength rapidly after application, especially when used with a highly absorbant adherand.

APPENDIX FOUR

The Results of Tensile Tests on Carbon Fibre Reinforced Cement Composites

Introduction.

In order to determine the relative efficiencies of cement plates reinforced with spread fibre and prepreg two series of tensile tests were carried out.

a) **Spread-Fibre Format.**

Thirty plate samples were made up using spread fibre veils as described in Chapter Four, these were tested to failure in tension and the results are recorded in Table A4.1.

b) **Prepreg Fibre Format.**

Eleven samples of cement composite plates reinforced with carbon fibre/PVA prepreg were tested to failure in tension. The results are recorded in Table A4.2.

Sample No.	V_f	Failure Stress.	$\sigma_f V_f$	Efficiency Factor
SF.01	0.0138	18.7	40.0	0.47
.02	0.0138	18.5	40.0	0.46
.03	0.0138	23.5	40.0	0.59
.04	0.0115	15.0	33.4	0.45
.05	0.0115	17.9	33.4	0.54
.06	0.0115	20.1	33.4	0.60
.07	0.0102	14.2	29.0	0.49
.08	0.0102	15.7	29.0	0.54
.09	0.0102	17.9	29.0	0.62
.10	0.0131	16.7	37.7	0.44
.11	0.0131	19.9	37.7	0.53
.12	0.0131	21.3	37.7	0.56
.13	0.0146	21.8	42.3	0.51
.14	0.0146	16.2	42.3	0.38
.15	0.0146	19.5	42.3	0.46
.16	0.0137	23.9	39.7	0.60
.17	0.0137	13.2	39.7	0.33
.18	0.0137	17.3	39.7	0.44
.19	0.0144	20.8	41.8	0.49
.20	0.0144	18.7	41.8	0.45
.21	0.0144	15.8	41.8	0.38
.22	0.0146	21.0	42.3	0.50
.23	0.0146	19.4	42.3	0.46
.24	0.0146	22.4	42.3	0.53
.25	0.0147	23.9	42.6	0.56
.26	0.0147	14.9	42.6	0.35
.27	0.0147	20.4	42.6	0.48
.28	0.0152	25.5	44.1	0.58
.29	0.0152	16.7	44.1	0.38
.30	0.0152	17.6	44.1	0.40
Mean	**0.0136**	**18.9**	**39.4**	**0.48**

(Coefficient of variation = 0.16)

Table A4.1 **Tensile Tests : Spread Fibre Format.**

Sample No.	V_f	Failure Stress.	$\sigma_f V_f$	Efficiency Factor
Pf.01	0.111	155.0	322.0	0.48
.02	0.083	71.7	241.0	0.30
.03	0.082	106.7	238.0	0.45
.04	0.089	79.0	258.0	0.31
.05	0.091	94.3	264.0	0.36
.06	0.091	108.3	264.0	0.41
.07	0.081	95.3	235.0	0.41
.08	0.095	105.0	276.0	0.38
.09	0.091	111.7	264.0	0.42
.10	0.085	95.0	247.0	0.38
.11	0.109	140.0	316.0	0.44
Mean	**0.092**	**105.6**	**266.8**	**0.40**

(Coefficient of variation = 0.14)

Table A4.2 Tensile Tests : Prepreg Fibre Format.

APPENDIX FIVE

Tensile Tests on Cement Composite Plates Reinforced Using Carbon Fibre/PVA Prepreg Produced by the 'Single Tow' Method

A5.1 Introduction.

In order to determine whether prepreg produced using the 'single tow' method could provide more efficient reinforcement than the flat sheet, 'filament wound', format used previously, a series of tensile tests was carried out on samples of carbon fibre/cement composite, reinforced with 'single tow' prepreg.

The results of these tests were then compared with the composite's theoretical strength to determine a tensile strength efficiency factor for the prepreg.

A5.2 Sample Format.

Twenty samples of carbon fibre/cement composite were produced, each measured approximately 300 x 50 x 6 mm and contained 34 tows of prepreg. The fibre volume fraction of the composite was therefore approximately 0.05 .

The samples were made up in plywood moulds by alternately brushing on layers of cement paste and placing prepreg tows. The top surface of each sample was trowelled smooth

Ordinary Portland Cement was used and a water/cement ratio of 0.45 was selected.

Before testing, aluminium end plates, measuring 75 x 50 mm were affixed using an epoxy resin adhesive. The purpose of these plates was to protect the ends of the samples from crushing in the jaws of the test machine.

The samples were tested at age 14 days.

A5.3 Test Format.

The samples were tested to failure in tension using an 'Instron 1195' test machine.

A 'Wallace' optical extensometer was used to record the extension of a 50 mm gauge length in the centre region of each sample.

The samples were held in the machine by means of two sets of grips, the bottom set was fixed in position and direction, the upper set was connected by means of a universal joint which allowed freedom of movement in two horizontal directions.

It was noted that as the grips were tightened onto the samples several small cracks were heard. This suggested that the samples were either not perfectly aligned or were perhaps not straight and that some stressing was being induced by the jaws of the test rig.

Graphs of applied load vs. gauge length extension were automatically recorded by the test machine.

A5.4 Results.

The Failure load of each sample was noted from the recorded graphs of Load vs Extension.

The theoretical failure load of the composite was the same in each case and was equal to $\sigma_{fu}A_f$. The composite strength efficiency factor could therefore be obtained by a comparison of the recorded failure load with the theoretical value.

The results are recorded in Table A5.1.

All of the samples failed in tension, rather than by delamination, but it was noted that in most cases failure was initiated in the region of the end plates rather than in the centre region of the sample.

This suggests the presence of stress concentrations around the jaws of the test rig and these could lead to premature failure of the samples prior to full composite strength being achieved. The recorded results will therefore represent a lower bound for the true strength of the composite.

In order to give an indication of the spread of the results the coefficient of variation for the efficiency factors was calculated.

Sample No.	Failure Load (N)	$\sigma_{fu}A_f$ (N)	Efficiency Factor.
.01	21000	43570	0.48
.02	20000		0.46
.03	17000		0.39
.04	19500		0.45
.05	20500		0.47
.06	19000		0.44
.07	19500		0.45
.08	19500		0.45
.09	17500		0.40
.10	21500		0.49
.11	21500		0.49
.12	18500		0.43
.13	17000		0.39
.14	19500		0.45
.15	17500		0.40
.16	20500		0.47
.17	21500		0.49
.18	22000		0.51
.19	23500		0.54
.20	22000		0.51
MEAN :	**19875**		**0.46**

(Coefficient of variation = 0.09)

Fibre Area $A_f = 34 \times 0.4419 = 15.0$ mm^2

Fibre Volume Fraction $V_f \simeq 0.05$

TABLE A5.1 Results of Tensile Tests on Carbon Fibre/Cement Composite.

A5.5 Discussion of Results.

From Table A5.1 it can be seen that the mean tensile strength efficiency of the composite samples reinforced with 'single tow' prepreg was 0.46.

It will be remembered that the mean tensile strength efficiency of composite samples reinforced with 'filament wound' prepreg was 0.40 and it would therefore appear that the use of carbon fibre/PVA prepreg produced by the single tow method allowed a more efficient use of the properties of the carbon fibres.

It is also interesting to note that the coefficient of variation of these results was significantly lower than that obtained previously for the filament wound prepreg format. This indicates that the mean value of tensile strength is more representative.

APPENDIX SIX

Determination of the Relationship Between Fibre Length and Strength

6.1 Introduction.

Tensile tests were carried out on samples of carbon fibre/PVA prepreg, produced by the 'single tow' method, to compare the relative strengths of different sample lengths.

Theory suggests that longer samples are statistically more likely to contain a critical defect than short samples and therefore their apparent strength should be lower.

6.2 Sample Format.

Samples of carbon fibre/PVA prepreg were produced using the single tow' method described in Chapter Five. The apparatus was at an interim stage of development and had been adapted slightly by replacement of the wire loop guide system with a plastic tube through which the fibre tow passed.

It was thought that this new arrangement may reduce fibre damage.

Lengths of prepreg were selected at random from several production runs in order to give an overall appraisal of the production method.

In all 15 short and 10 long samples were selected. The short samples were designated S.1 - 15, and the long samples L.1 - 10. Before testing card end tabs were affixed to the ends of the samples to prevent damage in the jaws of the test rig.

The gauge length of the short samples was 50 mm, the long samples had a gauge length of 200 mm.

6.3 Test Format.

The samples were tested to failure in tension using an 'Instron 1122' test machine. The rate of loading was controlled by the speed of cross-head displacement. A cross-head speed of 1.0 mm/min was selected, although with hindsight this seems rather high.

The test machine automatically plotted a graph of load vs. cross-head displacement.

6.4 Results.

The sample failure loads were noted from the graphs of load vs. extension plotted by the test rig. From these it was possible to determine the fibre stress at failure.

The ultimate values of fibre stress were then compared with the strength of the fibres as specified by the manufacturer to determine a tensile strength efficiency factor 'Q'.

The results are recorded in Table A6.1.

6.5 Discussion of Results.

The behaviour of the samples under test was the same in most cases. The graphs of Load vs Extension being linear until a first, partial failure occurred. This was not a catastrophic failure and the remaining fibres continued to take load until another partial failure took place. This process was often repeated 3 or 4 times before a final catastrophic failure occurred.

A number of samples however, experienced just one, catastrophic failure which often resulted in total disintegration of the sample.

From Table A6.1 it can be seen that the mean efficiency factors of the two sample test series were :

S Series. **Q = 0.47**

L Series. **Q = 0.36**

Sample No.	Failure Load (N)	Failure Stress (N/mm^2)	σ_{fu} (N/mm^2)	Efficiency. Factor 'Q'.
S.1	500.3	1132	2900	0.39
S.2	745.6	1687		0.58
S.3	323.7	733		0.25
S.4	421.8	955		0.33
S.5	765.2	1732		0.60
S.6	451.3	1021		0.35
S.7	765.2	1732		0.60
S.8	608.2	1376		0.47
S.9	618.0	1399		0.48
S.10	725.9	1643		0.57
S.11	569.0	1288		0.44
S.12	637.7	1443		0.50
S.13	686.7	1554		0.54
S.14	480.7	1088		0.38
S.15	765.2	1732		0.60
MEAN:	**604.3**	**1368**		**0.47**
	(Coefficient of variation = 0.24)			
L.1	412.0	932		0.32
L.2	637.7	1443		0.50
L.3	441.5	999		0.34
L.4	480.7	1088		0.38
L.5 .	451.3	1021		0.35
L.6	451.3	1021		0.35
L.7	382.6	866		0.30
L.8	461.1	1043		0.36
L.9	480.7	1088		0.38
L.10	431.6	977		0.34
MEAN:	**463.0**	**1049**		**0.36**
	(Coefficient of variation = 0.15)			

Fibre Area Af = 0.4419 mm^2

TABLE A6.1 Results of Tensile Tests on Carbon Fibre/PVA Prepreg.

It can be seen that the short samples generally sustained higher loads and consequently had a higher mean efficiency factor than the long samples.

As one would expect, the coefficient of variation for the longer samples was lower than that for the shorter samples.

The results of these tests supported the theory that long samples are statistically weaker than short samples due to the presence of defects.

APPENDIX SEVEN

Determination of the Tensile Strength and Elastic Modulus Efficiencies of Carbon Fibre/PVA Prepreg

A7.1 Introduction.

During the course of the research programme several series of tests were carried out on samples of carbon fibre/PVA prepreg. The results of these tests are reported here.

The first test series, designated 'P.0' was intended to determine whether the degree of fibre damage which occurred during the prepregging process could be reduced by the introduction of an alternative guide system, in this case the semicircular arch described in the main text.

The next two series of tests, designated 'P.3 & P.4' were carried out when it was felt that the high value of efficiency factor obtained in the 'P.0' Series may have been over optimistic.

The 'P.5' Series was carried out as a further confirmation of the results obtained previously.

A7.2 Sample Format.

In all cases the prepreg was produced using the 'single tow' method described in Chapter Seven.

In each case the sample to be tested was selected from the centre region of a 2m length of prepreg tape. Card end tabs were affixed to the ends of the samples using an epoxy resin adhesive.

The test samples were all of a standard format having a gauge length between the end tabs of 50mm.

The P.0 Series involved tests on 32 samples, the P.3, P.4, and P.5 Series had 20 samples each.

A7.3 Test Format.

The samples of carbon fibre/PVA prepreg were tested to failure in tension using an 'Instron 1122' test machine. The rate of loading was controlled by the speed of crosshead displacement.

A constant crosshead speed of 0.5mm/min was selected.

A graph of applied load vs. cross head displacement was automatically plotted for each sample by the test machine.

A7.4 Results.

P.0 Series.

The maximum tensile load sustained by each sample was recorded from the graphs plotted by the test machine. From these results the fibre tensile stress at failure was derived by dividing the applied load by the known fibre area of a single tow ($0.4419mm^2$).

The tensile strength efficiency factor for each sample was calculated by comparing the fibre stress at failure with the specified fibre strength ($2900\ N/mm^2$).

The results of the P.0 Series are recorded in Table A7.1 .

P.3 Series.

The results of tests on twenty samples are recorded in Table. A7.2.

The mode of failure of a number of samples consisted of a series of partial failures before total sample failure occurred. It was thought that these 'multiple failures' were caused by stress concentrations in the samples and therefore did not accurately represent the prepreg strength. The failure mode of the remainder of the samples was sudden and total.

The samples where 'multiple failure' took place are indicated by a '*' in the table of results.

Two values of mean efficiency were therefore calculated, the first for all samples, and the second excluding those samples where 'multiple failure' took place.

P.4 Series.

The P.4 Series of tests was carried out on samples prepared from the same batch of prepreg as the P.3 Series. The main difference between the two series being that the age of the samples when they were tested was 4 days in the case of the P.3 Series and 20 days in the case of the P.4 Series.

It was noted that the failure mode of all of the samples in the P.4 Series was sudden and catastrophic, none of the samples exhibited the multiple failure mode seen in the P.3 Series.

The results of the P.4 Series are recorded in Table A7.3 .

P.5 Series.

The results of the P.5 Series are recorded in Table A7.4 .

The failure mode of the P.5 Series was similar to that seen in the P.4 series in that none of the samples exhibited multiple failure.

A7.5 Discussion of Results.

From the results in Tables A7.1, A7.2, A7.3, & A7.4 the overall mean tensile strength efficiency of the carbon fibre/PVA prepreg can be derived as 0.63.

It will be noted that the results of the P.0 Series were consistently higher than the others and that a mean efficiency factor of 0.73 was obtained for these results, although the high cofficient of variation also idicates a wide spread of results.

Sample No.	Failure Load(N)	Failure Stress (N/mm^2)	σ_{fu} (N/mm^2)	Efficiency. Factor.
A.1	569	1288	2900	0.44
A.2	1177	2663		0.92
A.3	932	2109		0.73
A.4	1540	3485		1.20
A.5	667	1509		0.52
A.6	981	2220		0.77
A.7	1030	2330		0.80
A.8	863	1953		0.67
B.1	1020	2308		0.80
B.2	1256	2842		0.98
B.3	569	1288		0.44
B.4	1256	2842		0.98
B.5	1364	3087		1.06
B.6	755	1709		0.59
B.7	608	1376		0.47
B.8	628	1421		0.49
C.1	1256	2842		0.98
C.2	1059	2396		0.83
C.3	765	1731		0.60
C.4	814	1842		0.64
C.5	491	1111		0.38
C.6	726	1643		0.57
C.7	795	1799		0.62
C.8	540	1222		0.42
D.1	1324	2996		1.03
D.2	1158	2620		0.90
D.3	657	1487		0.51
D.4	1246	2820		0.97
D.5	961	2175		0.75
D.6	549	1242		0.43
D.7	1020	2308		0.79
D.8	1059	2396		0.83
MEAN :	**926**	**2096**		**0.73**

(Coefficient of variation = 0.31)

TABLE A7.1 **P.0 Series : Results of Tensile Tests on Carbon Fibre/PVA Prepreg.**

Sample No.	Failure Load(N)	Failure Stress (N/mm^2)	σ_{fu} (N/mm^2)	Efficiency. Factor.
P.3.01	579	1310	2900	0.45*
.02	731	1654		0.57
.03	768	1738		0.60
.04	427	966		0.33*
.05	591	1337		0.46*
.06	456	1032		0.36*
.07	755	1709		0.59
.08	952	2154		0.74
.09	648	1466		0.51*
.10	965	2184		0.75
.11	731	1654		0.57
.12	606	1371		0.47*
.13	748	1692		0.58
.14	888	2010		0.69
.15	562	1272		0.44*
.16	692	1566		0.54
.17	618	1399		0.48*
.18	613	1387		0.48*
.19	564	1276		0.44*
.20	456	1032		0.36*
MEAN :	668	1511		0.52
	(Coefficient of variation = 0.23)			
MEAN : (ex *)	803	1818		0.63
	(Coefficient of variation = 0.13)			

TABLE A7.2 P.3 Series : Results of Tensile Tests on Carbon Fibre/PVA Prepreg.

Sample No.	Failure Load(N)	Failure Stress (N/mm^2)	σ_{fu} (N/mm^2)	Efficiency. Factor.
P.4.01	726	1643	2900	0.57
.02	969	2193		0.76
.03	937	2120		0.73
.04	952	2154		0.74
.05	961	2175		0.75
.06	942	2132		0.74
.07	736	1666		0.57
.08	679	1537		0.53
.09	525	1188		0.41
.10	878	1987		0.69
.11	687	1555		0.54
.12	748	1693		0.58
.13	834	1887		0.65
.14	1010	2286		0.79
.15	645	1460		0.50
.16	567	1283		0.44
.17	790	1788		0.62
.18	814	1842		0.64
.19	871	1971		0.68
.20	623	1410		0.49
MEAN :	**795**	**1798**		**0.62**

(Coefficient of variation = 0.18)

TABLE A7.3 P.4 Series : Results of Tensile Tests on Carbon Fibre/PVA Prepreg.

Sample No.	Failure Load(N)	Failure Stress (N/mm^2)	σ_{fu} (N/mm^2)	Efficiency. Factor.
P.5.01	579	1310	2900	0.45
.02	626	1467		0.49
.03	865	1957		0.67
.04	716	1620		0.56
.05	873	1976		0.68
.06	790	1788		0.62
.07	637	1442		0.50
.08	813	1840		0.63
.09	643	1455		0.50
.10	725	1641		0.57
.11	726	1643		0.57
.12	741	1677		0.58
.13	901	2039		0.70
.14	797	1804		0.62
.15	461	1043		0.36
.16	589	1333		0.46
.17	878	1987		0.69
.18	802	1815		0.63
.19	777	1758		0.61
.20	863	1953		0.67
MEAN :	**740**	**1675**		**0.58**

(Coefficient of variation = 0.16)

TABLE A7.4 P.5 Series : Results of Tensile tests on Carbon Fibre/PVA Prepreg.

Series	Number of Samples	Elastic Modulus (N/mm^2)	Efficiency Factor.
P.0	32	142,325	0.66
P.3	20	91,055	0.42
P.4	20	100,600	0.48
P.5	20	81,495	0.38
MEAN :		**108,885**	**0.51**

TABLE A7.5 Summary of Prepreg Elastic Moduli and Efficiency Factors.

It is thought that this could be accounted for by the method of sample selection, for the P.0 Series considerable care was taken to select lengths of prepreg which were free from defects, for the remaining test series the samples were not chosen as carefully in order to give a more general appreciation of the prepreg properties.

When the rather crude nature of the prepregging process is taken into account a mean tensile strength efficiency factor of 0.63 is not considered to be an unreasonable lower bound value. It is thought that this could be improved, and the coefficient of variation reduced, by further refinements to the prepregging process.

Mean values of post matrix cracking elastic modulus were calculated for each test series and these are summarized in Table A7.5. These results were compared with the specified minimum elastic modulus for the carbon fibre of 215,000 N/mm^2 to produce an overall mean elastic modulus efficiency factor of 0.51.

APPENDIX EIGHT

Determination of the Tensile Properties of a Carbon Fibre Reinforced Cement Composite

A8.1 Introduction.

During the course of the research programme the properties of the carbon fibre reinforced cement composite material were determined and developed through many series of tensile tests.

The results of each test series formed the basis for the next development, either in the material itself, or in the test method, and by means of this step by step approach a composite with the desired properties was developed.

This appendix sets out briefly the reason for each test series in turn and gives the results in full. Many of the details of the fabrication and test methods were similar in all cases and these are not repeated except where differences occur.

A8.2 T.1 Series.

This series was used to determine the efficiency of 'single tow' prepreg when used as tensile reinforcement in a cement composite.

A8.2.1 Sample Preparation.

The cement plates were made up in open perspex moulds, which measured 300 x 50 x 3mm, by alternately brushing on a layer of cement paste (water/cement ratio 0.5) and placing a tow of prepreg until seventeen tows had been included. This gave a target fibre volume fraction of 0.05 (5.0%).

The cement plates were cured for seven days by storage in the moulds in damp conditions (ie. under damp sacking). After curing the plates were demoulded and allowed to dry.

When completely dry the plates were sanded smooth using an orbital sander and aluminium end plates measuring 50 x 75 mm were affixed using an epoxy resin adhesive.

The samples were tested at age 14 days.

A8.2.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' Test machine. The rate of loading was controlled by the speed of cross-head displacement and a constant cross-head speed of 1.0 mm/min was selected.

A graph of load vs. cross-head displacement was automatically plotted by the test machine.

A8.2.3 Results.

The maximum loads sustained by the samples were obtained from the graphs of load. vs. cross-head displacement. From these the maximum tensile stress sustained and the tensile strength efficiency factor for each sample were calculated.

From the slope of the graphs an estimate of the composite elastic modulus was made based upon a gauge length equal to the distance between the end plates.

A summary of the results is given in Table A8.1 .

A8.2.4 Conclusions.

The results of this test series were disappointingly low.

The mean tensile strength efficiency factor obtained was only 0.24 and the mean modulus efficiency was only 0.20 .

It was noted prior to testing that all the samples suffered from pronounced curvature and it was thought that this may have resulted in stress concentrations during testing.

The top surface of the samples was not quite smooth as it had only been trowelled smooth. It was possible that this roughness had also induced stress concentrations resulting in premature sample failure.

Sample No.	V_f	Failure Stress.	$\sigma_f V_f$	Efficiency Factor
T1.01	0.055	46.0	159.0	0.29
.02	0.040	27.0	115.0	0.23
.03	0.049	41.0	141.0	0.29
.04	0.050	36.0	144.0	0.25
.05	0.050	24.0	144.0	0.17
.06	0.050	39.0	146.0	0.27
.07	0.046	25.0	135.0	0.19
.08	0.051	44.0	147.0	0.30
.09	0.049	27.0	142.0	0.19
.10	0.049	33.0	143.0	0.23
MEAN.	**0.049**	**34.0**	**142.0**	**0.24**

(Coefficient of Variation = 0.19)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T1.01	0.055	2455	11825	0.21
.02	0.040	1730	8493	0.20
.03	0.049	2588	10535	0.25
.04	0.050	2000	10750	0.19
.05	0.050	1619	10750	0.15
.06	0.050	2194	10750	0.20
.07	0.046	1840	9890	0.19
.08	0.051	2476	10901	0.23
.09	0.049	2142	10535	0.20
.10	0.049	2128	10535	0.20
MEAN.	**0.049**	**2117**	**10585**	**0.20**

(Coefficient of Variation = 0.13)

TABLE A8.1 T.1 Series.

A8.3 T.2 Series.

This series of tests was used to see whether composite performance could be improved by forming a smooth upper surface to the samples and by reducing sample curvature.

A8.3.1 Sample Preparation.

The basic fabrication techniques were the same as used for the T.1 Series, but the samples were formed in perspex moulds provided with a close fitting perspex lid.

The water cement ratio used for this series was reduced to 0.4 as it was felt that the ratio used in the T.1 Series had a higher degree of workability than was really required.

Once sufficient prepreg and cement paste had been included the lid was pressed into place.

The samples were cured in their moulds for seven days, during this time the lids were kept firmly in place and the exposed ends of the samples were repeatedly sprayed with water to prevent drying.

An attempt was made to prevent the samples curving by placing weights on top of the moulds during the curing period.

Prior to testing the end regions of the samples were sanded smooth using an orbital sander and aluminium end plates measuring 75 x 50 mm were affixed using an epoxy resin adhesive.

The samples were tested at age 13 days.

A8.3.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test rig. During each test a 'Wallace' optical extensometer was used to record the extension of a 50mm gauge length in the centre region of each sample.

A graph of load vs. gauge length extension was automatically plotted by the test machine. A constant cross head speed of 0.5 mm/min was selected.

A8.3.3 Results.

The results of this test series are recorded in Table A8.2.

A8.3.4 Conclusions.

The results of this series were an improvement over those of the T.1 Series, but the tensile strength was still disappointingly low. The mean tensile strength efficiency factor improved from 0.24 to 0.30 and the elastic modulus efficiency improved dramatically from 0.20 to 0.85.

It was thought that much of the improvement was probably due to the use of two piece moulds, which as well as providing a smooth upper surface to the samples, also allowed the application of pressure during curing. It was considered that this pressure could have improved the compaction of the composite, increasing the bond between prepreg and cement and also forming a denser composite.

It was noted that the coefficient of variation had reduced considerably which indicated a product of more consistent properties.

units

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T2.01	0.049	46.0	141.0	0.33
.02	0.043	39.0	125.0	0.31
.03	0.041	37.0	120.0	0.31
.04	0.046	43.0	133.0	0.32
.05	0.047	38.0	137.0	0.28
.06	0.045	36.0	131.0	0.27
.07	0.043	34.0	124.0	0.27
.08	0.044	39.0	127.0	0.31
.09	0.047	35.0	135.0	0.26
.10	0.046	40.0	132.0	0.30
MEAN	**0.045**	**39.0**	**131.0**	**0.30**

(Coefficient of Variation = 0.08)

units

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T2.02	0.043	8179	9245	0.88
.03	0.041	6240	8880	0.70
.04	0.046	7423	9890	0.75
.05	0.047	9403	10148	0.93
.06	0.045	9375	9718	0.96
.07	0.043	8100	9159	0.88
.08	0.044	8330	9417	0.88
.10	0.046	8067	9804	0.82
MEAN	**0.045**	**8140**	**9534**	**0.85**

(Coefficient of Variation = 0.10)

TABLE A8.2 T.2 Series.

The sample curvature present in the T.1 Series was not eliminated by the measures taken during this series and could still be contributing to the premature sample failure.

Careful observation during the testing of the samples revealed a further possible cause of sample failure.

The aluminium end plates used to protect the composite in the jaws of the test machine extended beyond the length actually gripped by the test rig. As load was applied, the length of aluminium outside the test rig jaws was seen to curl away from the surface of the composite. As it did so it pulled with it portions of the cement matrix which were glued to it.

It seems likely that the damage caused by this contributed to the failure of samples and this was confirmed by the fact that most of the sample failures appeared to initiate in the region of the end plates.

Observation of the samples after testing showed that all had suffered from delamination between the prepreg and the cement matrix.

A8.4 T.3 Series.

As a result of the delamination observed in the last series it was originally intended to use this test series to determine whether the addition of PVA resin to the cement paste improved the bond between prepreg and cement.

However, because of the damage due to the curling end plates which was observed it was also decided to use this series to compare alternative end plate arrangements.

A8.4.1 Sample Preparation.

Ten composite samples were made up using the same method as the T.2 Series, with a target fibre volume fraction of 0.05.

'Timbabond 624' PVA resin was added to the cement paste in the proportions resin/water/cement : 0.1/0.35/1.0. The addition of the PVA allowed the water/cement ratio to be reduced slightly without reducing the workability.

As before, the samples were cured for seven days in their moulds with the lids held in place by weights in an effort to reduce curvature.

To determine whether any 'end effects' could be reduced two of the samples were 'necked' to 25 mm in their centre region. It was thought that this would encourage failure away from any stress concentrations around the jaws of the test rig which may have caused premature failure in earlier tests.

Prior to testing the end region of each sample was sanded smooth and aluminium end plates were affixed. Four of the samples were fitted with the standard 50 x 75mm plates, the remaining six samples, including the two necked ones, were fitted with plates which measured 50 x 50 mm.

The smaller end plates could be entirely contained within the jaws of the test rig and it was thought that this would eliminate the problem experienced before.

The samples were tested at age 14 days.

A8.4.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected.

A 'Wallace' optical extensometer was used to record the extension of a 50mm gauge length which had been marked in the centre region of each sample.

A8.4.3 Results.

The results of the T.3 Series are recorded in Table A8.3.

It should be noted that the fibre volume fractions of the two necked samples (T3.09 & .10) were calculated from the dimensions of the samples before they were necked. The V_f values given for these samples are therefore only estimates.

A8.4.4 Conclusions.

Examination of the samples after testing revealed no evidence of delamination between the prepreg tows and the cement matrix. This appeared to indicate that the bond between the two components had been improved considerably by the addition of the PVA resin to the cement paste.

This was confirmed by comparison of the results of the first four samples with the previous test series where no PVA was added. The results of this series showed an improvement in composite tensile strength efficiency of 30 %.

	Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
50 x	T3.01	0.048	56.0	139.2	0.40
75 mm	.02	0.045	57.0	130.5	0.44
end	.03	0.045	46.0	130.5	0.35
plates	.04	0.046	49.0	133.4	0.39
	MEAN	**0.046**	**52.0**	**133.4**	**0.39**
			(Coefficient of Variation = 0.09)		
50 x	T3.05	0.047	70.0	136.3	0.51
50 mm	.06	0.042	49.0	121.8	0.40
end	.07	0.045	65.0	130.5	0.50
plates	.08	0.044	59.0	127.6	0.46
	MEAN	**0.045**	**61.0**	**129.1**	**0.47**
			(Coefficient of Variation = 0.10)		
	T3.09	0.045	70.0	130.5	0.54
	.10	0.041	66.0	118.9	0.56
	MEAN	**0.043**	**68.0**	**124.7**	**0.55**

TABLE A8.3(a) T.3 Series. Tensile Strength.

	Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
50 x	T3.01	0.048	7960	10320	0.77
75 mm	.02	0.045	8030	9675	0.83
end	.03	0.045	7000	9675	0.72
plates	.04	0.046	9385	9890	0.95
	MEAN	**0.046**	**8094**	**9890**	**0.82**
			(Coefficient of Variation = 0.12)		
50 x	T3.05	0.047	8930	10105	0.88
50 mm	.06	0.042	6278	9030	0.70
end	.07	0.045	7930	9675	0.82
plates	.08	0.044	7350	9460	0.78
	MEAN	**0.045**	**7622**	**9567**	**0.80**
			(Coefficient of Variation = 0.09)		
	T3.09	0.045	13720	9675	1.42
	.10	0.041	9575	8815	1.09
	MEAN	**0.043**	**11648**	**9245**	**1.26**

TABLE A8.3(b) T.3 Series. Elastic Modulus.

The group of samples with the smaller end plate arrangement reached significantly higher failure stresses than the 'control' group with the larger plates. The elastic modulus efficiency of the two groups was very similar.

The results of the tests on the two necked samples indicated even higher values of both tensile strength and modulus. It was possible, however, that the method of calculating the fibre volume fraction from the dimensions of the un-necked samples may have resulted in an underestimate.

If the fibre distribution was not entirely even and the fibres were concentrated in the centre of the sample then the actual fibre volume fraction of the necked samples would be greater than that of the original sheet. An underestimate of the fibre volume fraction would lead to an overestimate of efficiency.

Both 'necked' samples achieved modulus efficiency factors in excess of 1.0. This suggested that such an over estimate may have occurred.

This series of tests was considered to be particularly useful. The results showed that the addition of PVA to the cement paste had apparently prevented composite delamination and had improved performance. The tests also showed that the end plate arrangement had a significant effect upon the apparent composite performance.

It was noted that all the samples suffered from a degree of curvature. Sample T3.06 was particularly badly affected and it can be seen from the results in Table A8.3(a) that this sample did have the lowest tensile strength efficiency in its group. It seemed likely that sample curvature was having an effect upon the results, but it was not clear at this stage what was causing it.

It was felt that although the use of necked samples had apparently resulted in improved results, the uncertainty over the calculation of fibre volume fraction had created difficulties in the interpretation of these.

A8.5 T.4 Series.

This series of tests was carried out to confirm the results of the T.2 Series and to confirm that the use of shortened end plates gave improved results.

Further attempts were made to reduce sample curvature.

A8.5.1 Sample Preparation.

The composite samples were made up using the same methods as the T.2 Series. A water/cement ratio of 0.4 was used and no PVA resin was added to the cement paste.

The samples were cured, as before, in their moulds for seven days.

After demoulding the samples were placed upside down between two flat perspex sheets. Weights were then placed on top of this. After a further two days the samples were removed from between the sheets and were examined. At this point all the samples appeared to be flat.

The ends of the samples were sanded and 50 x 50mm aluminium end plates were affixed.

Before testing the samples were examined again and although most had remained flat a number did have a noticable curvature, especially sample T4.10.

The samples were tested at age 14 days.

A8.5.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.5.3 Results.

The results of the T.4 Series are recorded in Table A8.4.

A8.5.4 Conclusions.

The mean tensile strength efficiency factor of this series showed an improvement of 10 % over the results of the T.2 Series. It was considered that this could be attributed to the amended end plate arrangement.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T4.01	0.049	45.6	129.9	0.35
.02	0.042	36.1	120.9	0.30
.03	0.047	43.9	136.6	0.32
.04	0.049	45.3	129.9	0.35
.05	0.040	37.2	114.8	0.32
.06	0.045	40.6	131.1	0.31
.07	0.042	46.0	123.0	0.37
.08	0.041	40.2	118.3	0.34
.09	0.039	42.4	112.5	0.38
.10	0.041	33.0	117.7	0.28
MEAN	**0.043**	**41.0**	**123.5**	**0.33**

(Coefficient of Variation = 0.09)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T4.01	0.049	-	9632	-
.02	0.042	-	8966	-
.03	0.047	6024	10127	0.60
.04	0.049	6346	9632	0.66
.05	0.040	5547	8514	0.65
.06	0.045	-	9718	-
.07	0.042	5280	9116	0.58
.08	0.041	7006	8772	0.80
.09	0.039	6000	8342	0.72
.10	0.041	6183	8729	0.71
MEAN	**0.042**	**6055**	**9033**	**0.67**

(Coefficient of Variation = 0.11)

TABLE A8.4 T.4 Series.

The mean elastic modulus efficiency was suprisingly lower than that of the T.2 Series, the reason for this was not immediately apparent. Values of elastic modulus were not calculated for samples T4.01 & .02 due to a malfunction of the extensometer, the graph of load vs extension for sample T4.06 exhibited very strange behaviour including negative extension under load !

Examination of the samples after testing confirmed that all had suffered from delamination. This further supported the theory that the use of PVA in the cement paste improved composite performance by improving the prepreg/matrix bond.

It was noted that the sample which exhibited the worst degree of curvature prior to testing (T4.10) had the lowest tensile strength efficiency factor.

A8.6 T.5 Series.

The T.5 Series was used to confirm that the addition of PVA to the cement paste improved composite performance as observed in the T.3 Series.

A8.6.1 Sample Preparation.

The samples were made up as for the T.3 Series. Seventeen tows of prepreg were included in each to give a target fibre volume fraction of 0.05.

The resin/water/cement ratio used was 0.1/0.35/1.0 .

In an attempt to reduce sample curvature, the same precautions as used for the T.4 Series were employed.

The samples were tested at age 15 days.

A8.6.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.6.3 Results.

The results of the T.5 Series are recorded in Table A8.5.

A8.6.4 Conclusions.

The mean tensile strength efficiency factor of these samples was 0.50. This compares with the value of 0.47 obtained in the T.3 Series for similar samples.

The mean elastic modulus efficiency of 0.92 showed an improvement over the results of the T.3 Series and indicated that the composite was behaving almost in accordance with the theoretical model.

The results were a significant improvement over those of the T.4 Series, with an increase in strength efficiency of over 50% and a 37% increase in modulus efficiency.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T5.01	0.049	73.8	143.0	0.52
.02	0.049	68.7	142.4	0.48
.03	0.047	62.2	135.4	0.46
.04	0.047	62.9	136.9	0.46
.05	0.049	73.9	140.7	0.53
.06	0.048	70.5	139.5	0.51
.07	0.047	69.3	135.4	0.51
.08	0.049	61.5	142.4	0.43
.09	0.045	59.6	129.6	0.46
.10	0.045	80.3	130.5	0.62
MEAN	**0.047**	**68.3**	**137.4**	**0.50**

(Coefficient of Variation = 0.10)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T5.01	0.049	10090	10600	0.95
.02	0.049	8175	10557	0.77
.03	0.047	9562	10041	0.95
.04	0.047	8979	10148	0.88
.05	0.049	9931	10428	0.95
.06	0.048	9854	10342	0.95
.07	0.047	8572	10041	0.85
.08	0.049	10464	10557	0.99
.09	0.045	9325	9611	0.97
.10	0.045	8564	9675	0.89
MEAN	**0.047**	**9352**	**10191**	**0.92**

(Coefficient of Variation = 0.07)

Table A8.5 T.5 Series.

These results confirmed beyond doubt, that the addition of PVA to the matrix made a significant contribution to composite strength by eliminating the delamination which had occurred between prepreg and cement.

The problem of sample curvature was again present. Some thought was given to this and a possible explanation was derived.

Because of the method of sample fabrication, the prepreg reinforcement tended to be concentrated in the lower part of the samples with a corresponding concentration of cement paste towards the top.

As the cement paste dried and set it would shrink. The dense fibre reinforcement in the lower half of the sample could restrict the amount of shrinkage in this area. In the top half the cement was less restrained and could shrink more. This would produce a degree of differential shrinkage between the top and bottom of the samples which would tend to cause the sample to curve upwards.

It was noted that sample curvature was in deed always upwards which gave support to this theory.

A8.7 T.6 Series.

An attempt to overcome the problem of sample curvature was made by the use of thicker samples.

A8.7.1 Sample Preparation.

Ten cement plates which measured 200 x 50 x 6mm were made up in two piece perspex moulds.

The method of fabrication was identical to that used in the T.5 Series, but in order to achieve a target volume fraction of 0.05, 34 tows of prepreg were included.

The samples were cured and end plates affixed as per the T.5 Series.

The samples were tested at age 14 days.

A8.7.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.7.3 Results.

The results of the T.6 Series are recorded in Table A8.6.

A8.7.4 Conclusions.

Although the samples showed no signs of curvature prior to testing the tensile strength efficiency which was achieved was identical to that of the T.5 Series.

The elastic modulus efficiency was also similar to the result obtained in the T.5 Series.

The results were taken as further confirmation of the benefits of adding PVA to the cement paste. The tests series also showed that by the use of consistent fabrication techniques a composite of consistent properties could be produced.

A8.8 T.7 Series.

Because of the water solubility of the Timbabond 624 PVA which was being used there was some concern over its potential long term stability in exposed conditions.

This test series was designed to determine whether the same improvements in composite performance could be achieved if a non-soluble PVA was used as the additive to the cement paste.

A8.8.1 Sample Preparation.

The method of sample fabrication was basically the same as the T.6 Series and the same size of sample was used (200 x 50 x 6mm).

Timbabond 636 resin was added to the cement paste to give a resin/water/cement ratio of 0.1/0.45/1.0.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T6.01	0.049	67.1	142.6	0.47
.02	0.045	64.4	132.0	0.49
.03	0.047	61.8	135.6	0.46
.04	0.047	69.1	136.9	0.51
.05	0.048	65.8	138.2	0.48
.06	0.048	71.6	138.6	0.52
.07	0.047	70.6	136.8	0.52
.08	0.047	73.7	136.7	0.54
.09	0.048	69.3	138.9	0.50
.10	0.046	63.0	132.3	0.48
MEAN	**0.047**	**67.6**	**136.9**	**0.50**

(Coefficient of Variation = 0.05)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T6.01	0.049	9954	10535	0.94
.02	0.045	9323	9675	0.96
.03	0.047	9577	10105	0.95
.04	0.047	8515	10105	0.84
.05	0.048	10754	10320	1.04
.06	0.048	9088	10320	0.88
.07	0.047	9304	10105	0.92
.08	0.047	9654	10105	0.96
.09	0.048	9108	10320	0.88
.10	0.046	9346	9890	0.94
MEAN	**0.047**	**9462**	**10149**	**0.93**

(Coefficient of Variation = 0.06)

TABLE A8.6 T.6 Series.

This type of resin had the property of being initially soluble in water, but over a period of time becoming increasingly water resistant.

It was necessary to increase the water/cement ratio of the paste as it was found that the use of '636' as an additive produced a cement paste with much reduced workability.

Curing conditions and end plate arrangements were identical to the T.6 Series.

The samples were tested at age 14 days.

A8.8.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.8.3 Results.

The results of the T.7 Series are recorded in Table A8.7.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T7.01	0.046	49.0	133.4	0.37
.02	0.047	54.9	136.3	0.40
.03	0.044	62.2	127.6	0.49
.04	0.048	53.2	139.2	0.38
.05	0.047	49.0	136.3	0.36
.06	0.046	55.3	133.4	0.41
.07	0.049	51.1	142.1	0.36
.08	0.048	63.3	139.2	0.45
.09	0.048	66.1	139.2	0.47
.10	0.043	58.8	124.7	0.47
MEAN	**0.047**	**56.3**	**135.1**	**0.42**

(Coefficient of Variation = 0.12)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T7.01	0.046	4043	9890	0.41
.02	0.047	7120	10105	0.70
.03	0.044	9758	9460	1.03
.04	0.048	6071	10320	0.59
.05	0.047	5673	10105	0.56
.06	0.046	8200	9890	0.83
.07	0.049	5959	10535	0.57
.08	0.048	6185	10320	0.60
.09	0.048	5096	10320	0.49
.10	0.043	7910	9245	0.86
MEAN	**0.047**	**6602**	**10105**	**0.66**

(Coefficient of Variation = 0.29)

TABLE A8.7 T.7 Series.

A8.8.4 Conclusions.

The addition of Timbabond 636 to the cement paste did produce an increase in composite performance compared to those cases where no PVA had been added (T.4 Series). The improvement in properties was however nowhere near as great as when the water soluble Timbabond 624 was used.

It was also noted that there was a considerable increase in the variation of the results when the '636' resin was used.

Although the long term stability of '624' would still need to be investigated it was considered at this stage that the reduction in composite properties resulting from the use of '636' was not acceptable. Consequently it was decided not to adopt the use of this alternative resin.

A8.9 T.8 Series.

Following on from the T.5 Series, this series was used to determine whether a more even distribution of fibres throughout the composite could reduce the curvature of thin (3 mm) samples.

The test series was also used to determine whether curing the cement composite under water would result in improved properties.

A8.9.1 Sample Manufacture.

The method of sample fabrication was basically the same as that used for the T.5 Series, except that a thicker than normal layer of cement paste was applied to the bottom of the mould before the first tow of prepreg was placed.

It was thought that this would result in the prepreg being distributed more evenly above and below the neutral axis.

Timbabond 624 was added to the cement paste in the usual ratio of 0.1/0.35/1.0.

The first five samples (T8.01 - .05) were cured in their moulds under water. The remaining samples were cured by the usual method of storing them in their moulds and keeping the exposed ends damp.

After curing for seven days all the samples were demoulded and they were then stored under pressure between two sheets of perspex to prevent them curving.

Before testing the end zones were sanded smooth and aluminium end plates were affixed.

It was noted that despite the revised fabrication technique and the application of weights the samples were markedly curved.

The samples were tested at age 15 days.

A8.9.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.9.3 Results.

The results of the T.8 Series are recorded in Table A8.8.

A8.9.4 Conclusions.

The was no significant difference between the tensile strength efficiency of the samples cured in different conditions. The modulus efficiency of the wet cured samples was however slightly higher than those that were damp cured.

The overall tensile strength efficiencies showed a considerable improvement over the results of the T.5 and T.6 Series.

It was thought that the general improvement in composite strength may have been due to the more even fibre distribution, even though this did not reduce sample curvature. It was possible that the previous uneven distribution was resulting in uneven stressing of the composite and this could have caused premature failure.

A8.10 T.9 Series.

This limited series of tests was used to determine whether composite properties improved with age.

A8.10.1 Sample Preparation.

The samples were made up using the same techniques as the T.8 Series to produce an even fibre distribution.

The proportions of the cement paste were the same as the T.8 Series, but the number of prepreg tows had to be reduced due to a shortage of carbon fibre. Fourteen tows were used in each sample to give a target fibre volume fraction of 0.04.

The samples were cured in their moulds for seven days in damp conditions, they were then demoulded and the curing continued.

Before testing aluminium end plates were affixed.

The samples were tested at age 41 days.

A8.10.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

	Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
Wet Cure	T8.01	0.043	75.4	124.4	0.61
	.02	0.041	55.5	118.6	0.47
	.03	0.044	79.0	128.5	0.62
	.04	0.043	70.8	123.3	0.57
	.05	0.045	72.5	129.3	0.56
	MEAN	**0.043**	**70.6**	**124.7**	**0.57**
			(Coefficient of Variation = 0.10)		
Damp Cure	T8.06	0.043	66.9	123.5	0.54
	.07	0.043	76.3	124.1	0.61
	.08	0.040	69.9	116.3	0.60
	.09	0.040	70.4	116.9	0.60
	.10	0.047	72.5	136.1	0.53
	MEAN	**0.042**	**71.2**	**123.0**	**0.58**
			(Coefficient of Variation = 0.07)		

	Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
Wet Cure	T8.01	0.043	8459	9224	0.92
	.02	0.041	7134	8794	0.81
	.03	0.044	8733	9525	0.92
	.04	0.043	9056	9138	0.99
	.05	0.045	8800	9589	0.92
	MEAN	**0.043**	**8436**	**9245**	**0.91**
			(Coefficient of Variation = 0.07)		
Damp Cure	T8.06	0.043	7088	9159	0.77
	.07	0.043	7715	9202	0.84
	.08	0.040	8369	8622	0.97
	.09	0.040	8592	8665	0.99
	.10	0.047	8620	10084	0.85
	MEAN	**0.042**	**8077**	**9116**	**0.88**
			(Coefficient of Variation = 0.10)		

TABLE A8.8 T.8 Series.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.10.3 Results.

The results of the T.9 Series are recorded in Table A8.9.

A8.10.4 Conclusions.

When the results of this series were compared with those of the T.8 Series it could be seen that there was apparently a slight improvement in composite tensile strength efficiency.

The modulus efficiency factor of 0.97 was very close to unity and suggested that the material was following the Rule of Mixtures very closely although the variation of the elastic modulus was quite large.

The results seem to indicate that an improvement in composite properties could be expected with age though a more comprehensive series of tests would be required to demonstrate this more thoroughly.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T9.01	0.043	68.8	124.7	0.55
.02	0.035	64.6	102.7	0.63
.03	0.039	69.6	114.0	0.61
.04	0.040	63.0	114.8	0.55
.05	0.041	71.7	118.0	0.61
MEAN	**0.040**	**67.5**	**114.8**	**0.59**

(Coefficient of Variation = 0.06)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T9.01	0.043	8193	9245	0.89
.02	0.035	7620	7611	1.00
.03	0.039	10583	8450	1.25
.04	0.040	7994	8514	0.94
.05	0.041	6921	8751	0.79
MEAN	**0.040**	**8262**	**8514**	**0.97**

(Coefficient of Variation = 0.18)

TABLE A8.9 T.9 Series.

A8.11 T.11 Series.

The fibre volume fractions of the previous series had been in the region of 0.04 - 0.05. In order to increase the properties of the composite to a level at which it became structurally viable it was decided to determine whether an increase in the fibre volume fraction produced a corresponding, proportional increase in the composite properties.

A8.11.1 Sample Preparation.

Ten plate samples, measuring 300 x 50 x 3mm were made up using the two piece perspex moulds, the basic method being the same as that used for the T.9 Series.

To achieve the desired target fibre volume fraction of 0.10, 34 tows of prepreg would be required. In an attempt to ensure that the target was met, 40 tows were included.

In order to include the higher number of tows the workability of the cement paste had to be increased. Consequently the water cement ratio was increased from 0.35 to 0.45. No corresponding increase was made in the resin content and so the overall cement paste proportions were resin/water/cement : 0.1/0.45/1.0 .

Because of the high V_f and expected high composite strengths, it was thought possible that sample failure could occur due to break down of the bond between the end plates and the sample before tensile failure took place.

Six of the samples were therefore necked down to 25mm to encourage tensile failure of the sample in their centre region.

Before testing aluminium end plates were affixed using an epoxy resin adhesive.

A8.11.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.11.3 Results.

The results of the T.11 Series are recorded in Table A8.10.

A8.11.4 Conclusions.

An increase in the fibre content of the composite did result in an increase in the composite properties. However, the increase in the tensile strength was not as much as had been expected and this was reflected by the tensile strength efficiency factors which were lower than some of the previous 'low V_f' test series.

The use of the higher fibre volume fraction did reduce the coefficient of variation of the results to approximately half of that of the previous series.

	Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
	T11.01	0.094	133.4	272.6	0.49
	.02	0.091	121.0	263.9	0.46
	.03	0.096	127.3	278.4	0.46
	.04	0.098	135.4	284.2	0.48
	MEAN	**0.095**	**129.2**	**275.5**	**0.47**
			(Coefficient of Variation = 0.03)		
(Necked)	T11.05	0.089	114.1	258.1	0.44
	.06	0.084	117.5	243.6	0.48
	.07	0.086	109.6	249.4	0.44
	.08	0.085	98.3	246.5	0.40
	.09	0.086	101.0	249.4	0.40
	.10	0.080	97.8	232.0	0.42
	MEAN	**0.085**	**106.2**	**246.5**	**0.43**
			(Coefficient of Variation = 0.07)		

	Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
	T11.01	0.094	24389	20210	1.21
	.02	0.091	15844	19565	0.81
	.03	0.096	18924	20640	0.92
	.04	0.098	19226	21070	0.91
	MEAN	**0.095**	**19596**	**20371**	**0.96**
			(Coefficient of Variation = 0.18)		
(Necked)	T11.05	0.089	21637	19135	1.13
	.06	0.084	18210	18060	1.01
	.07	0.086	17343	18490	0.94
	.08	0.085	18720	19275	1.02
	.09	0.086	19190	18490	1.04
	.10	0.080	16010	17200	0.93
	MEAN	**0.085**	**18518**	**18275**	**1.01**
			(Coefficient of Variation = 0.07)		

TABLE A8.10 T.11 Series.

Examination of the samples after testing revealed obvious signs of delamination between the prepreg and the cement. This would account for the lower strengths as it had been shown in previous tests, that where delamination occurred the composite performance had always been reduced.

It was thought that the reason for this delamination may be the reduced resin/water ratio of this series.

It was noted that despite the extra prepreg which had been included, the fibre volume fraction of the composite did not reach the target of 0.10. It was felt that this was because there seemed to be a practical limit on the amount of prepreg which could be included in a 3mm thick plate, any greater amount of reinforcement simply resulted in thicker samples without significantly increasing the fibre volume fraction.

A8.12 T.12 Series.

A limited number of tests was carried out to determine whether restoring the resin/water ratio of the cement paste to the equivalent of 0.1/0.35 reduced the degree of delamination which had been observed in the T.11 Series.

Sample fabrication was carried out as described for the T.11 Series, except that the number of tows of prepreg was reduced to 35.

The resin/water/cement ratio of the cement paste was 0.13/0.45/1.0.

The samples were cured in their moulds in damp conditions for seven days and were then demoulded and aluminium end plates were affixed.

A8.12.1 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.12.2 Results.

The results of the T.12 Series are recorded in Table A8.11.

A8.12.3 Conclusions.

Examination of the samples after testing revealed little sign of delamination between the prepreg and the cement. This confirmed that the resin/water ratio was critical and suggested that a further increase in PVA content may bring about further improvements in composite performance.

The mean tensile strength efficiency factor had increased to 0.52 which was more in line with the earlier results but was still not as high as the T.9 series where an efficiency factor of 0.59 had been achieved.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T12.01	0.090	152.0	261.0	0.58
.02	0.086	117.0	251.0	0.47
.03	0.086	125.0	248.0	0.50
.04	0.101	156.0	293.0	0.53
MEAN	**0.091**	**137.0**	**263.0**	**0.52**

(Coefficient of Variation = 0.09)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T12.01	0.090	16664	19350	0.86
.02	0.086	13940	18490	0.75
.03	0.086	22140	18490	1.20
.04	0.101	21700	21715	1.00
MEAN	**0.091**	**18611**	**19511**	**0.95**

(Coefficient of Variation = 0.20)

TABLE A8.11 T.12 Series.

This series of tests confirmed the observation of the previous test series that the increase in composite properties was not directly proportional to the increase in the fibre volume fraction.

A8.13 T.14 Series.

Following on from the results of the T.12 Series, this series of tests was used to determine whether a further increase in the PVA content of the cement paste would produce a further improvement in composite properties.

A8.13.1 Sample Preparation.

Ten samples were made up in perspex moulds, each measured 300 x 50 x 3mm. Thirty five tows of prepreg were included in each sample, to give a target fibre volume fraction of 0.10.

The water cement ratio was maintained at 0.45. The resin/water ratio was increased from 0.13/0.45 to 0.2/0.45, this represented an increase of over 50%.

The samples were cured in their moulds in damp conditions for seven days. They were then demoulded and aluminium end plates were affixed.

The samples were tested at age 23 days.

A8.13.2 Testing.

The samples were tested to failure in tension using an 'Instron 1195' test machine. A constant cross head speed of 0.5 mm/min was selected for all the samples.

The extension of each sample was recorded by means of a 'Wallace' optical extensometer calibrated to a gauge length of 50 mm in the centre region of each sample.

The test machine automatically plotted a graph of load vs. gauge length extension.

A8.13.3 Results.

The results of the T.14 Series are recorded in Table A8.12 .

A8.13.4 Conclusions.

Contrary to expectations the mean tensile strength efficiency of the composite samples was less than had been recorded for the T.12 Series. The mean elastic modulus efficiency was similar to the results of the previous series. No calculation of elastic modulus was made for sample T14.06 as the load-extension graph for this sample seemed somewhat erratic.

Behaviour of the samples under test was slightly different, in that, unlike previous tests where, just prior to failure, an indication that failure was iminent was given through audible cracking or a slight fall off in the gradient of the load/extension graph, in this series there was no warning and failure was sudden and catastrophic.

Sample No.	V_f	Tensile Strength.	$\sigma_f V_f$	Efficiency Factor
T14.01	0.081	110.6	234.9	0.47
.02	0.083	134.1	240.7	0.56
.03	0.083	98.9	240.7	0.41
.04	0.071	90.4	205.9	0.44
.05	0.077	91.7	223.3	0.41
.06	0.082	90.4	237.8	0.38
.07	0.088	111.0	255.2	0.43
.08	0.076	101.0	220.4	0.46
.09	0.082	109.8	237.8	0.46
.10	0.072	95.6	208.8	0.46
MEAN	**0.080**	**103.4**	**230.6**	**0.45**

(Coefficient of Variation = 0.11)

Sample No.	V_f	Elastic Modulus.	$E_f V_f$	Efficiency Factor
T14.01	0.081	21060	17415	1.21
.02	0.083	15330	17845	0.86
.03	0.083	17104	17845	0.96
.04	0.071	13180	15265	0.86
.05	0.077	18120	16555	1.09
.06	0.082	-	17630	-
.07	0.088	13460	18920	0.71
.08	0.076	15154	16340	0.93
.09	0.082	16290	17630	0.92
.10	0.072	14308	15480	0.92
MEAN	**0.080**	**16001**	**17093**	**0.94**

(Coefficient of Variation = 0.15)

TABLE A8.12. T.14 Series.

Examination of the samples after testing revealed little evidence of delamination and the failure modes all appeared to be primarily tensile.

It would appear that a significant increase in the PVA content of the cement paste had not produced a corresponding improvement in composite properties.

From the results of the T.11, T.12 and this current test series it would appear that both an increase in PVA content and a decrease have resulted in lower composite properties.

It was considered likely that there was an optimum PVA content for maximum composite properties which it would be possible to determine, but this would require an extensive series of tests to compare the performance of composites with a range of PVA contents.

This was the last series of tensile tests on samples of carbon fibre reinforced cement composite to be carried out.

APPENDIX NINE

Photographs

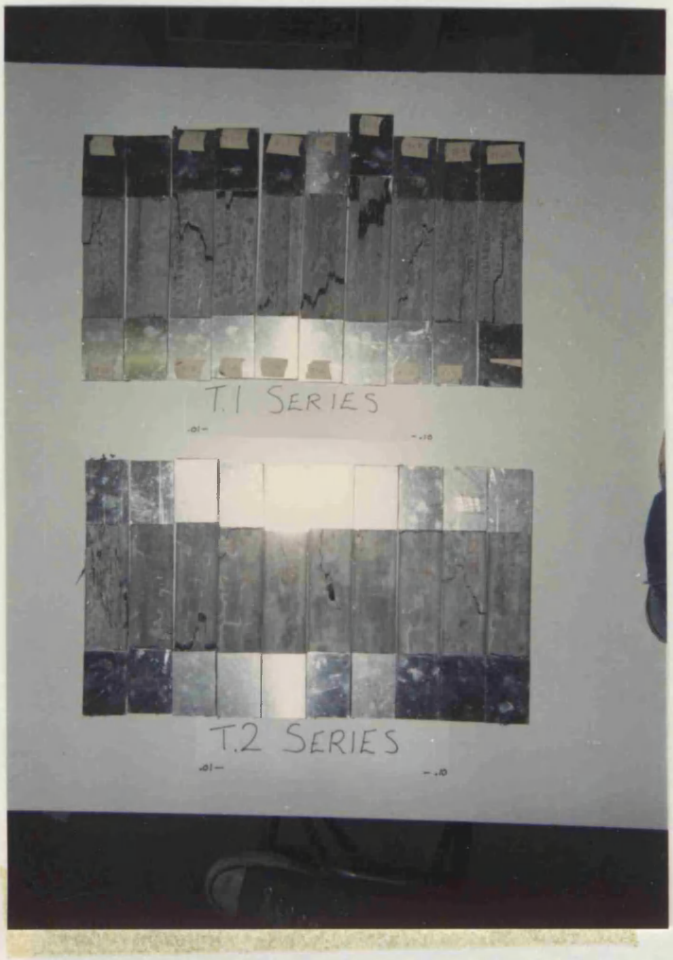
A9.1 Introduction.

This appendix includes a number of photographs taken during the course of the research. In particular it contains photographs of test specimens after failure and also a number of photographs which were taken using a Scanning Electron Microscope.

A9.2 Tensile Tests.

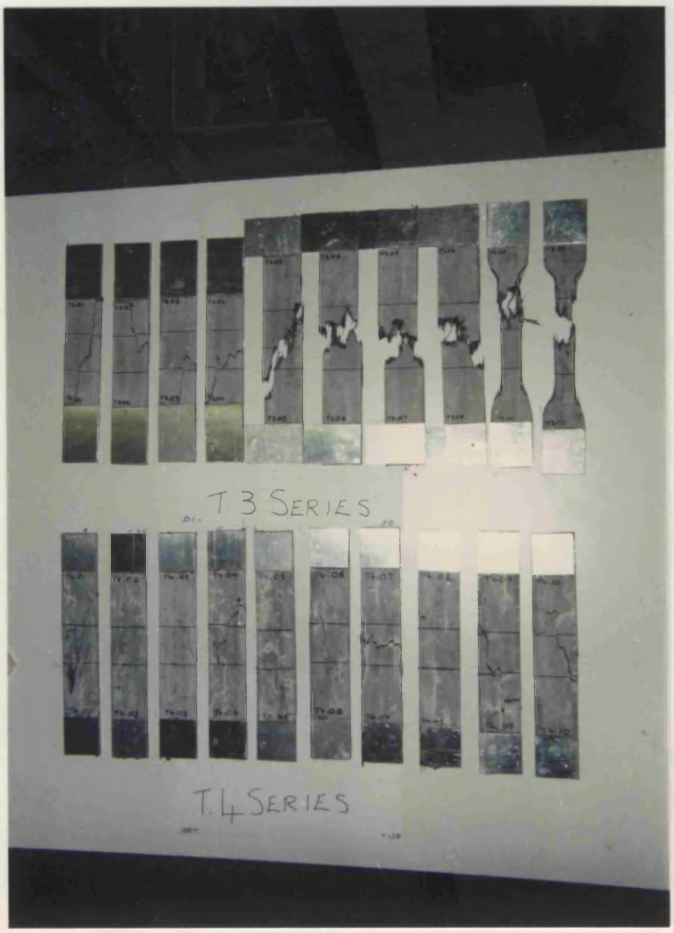
The photographs in this section show the samples of carbon fibre reinforced cement after they had been tested to failure in tension.

The sample reference numbers refer to the tensile test series which are described in full in Appendix Eight and which are referred to in the main text in Chapter Six.



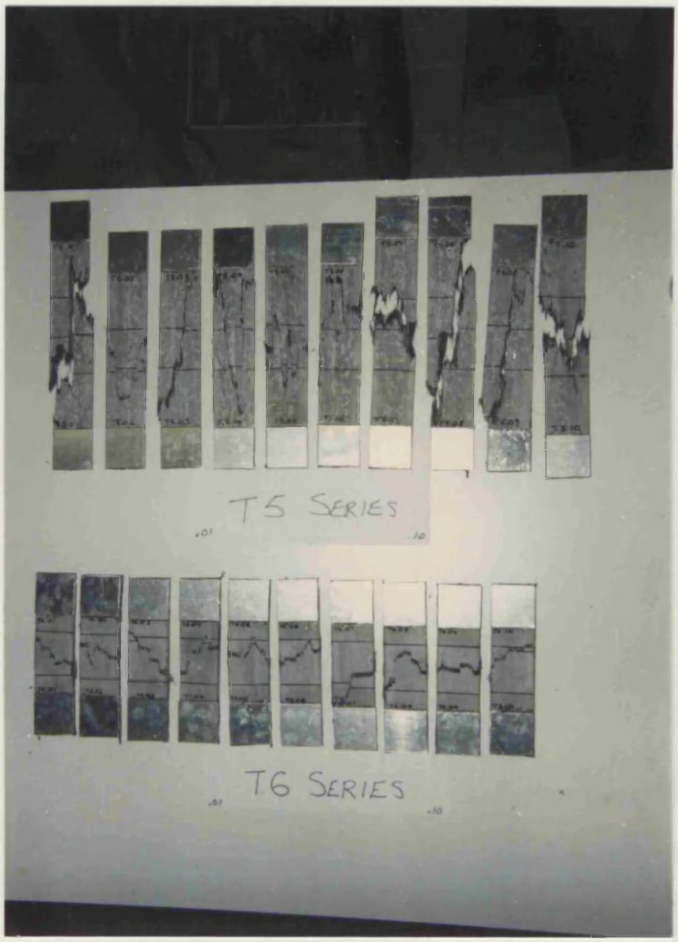
Photograph No. 01

Samples from the T.1 and T.2 Series where no PVA was added to the cement paste.



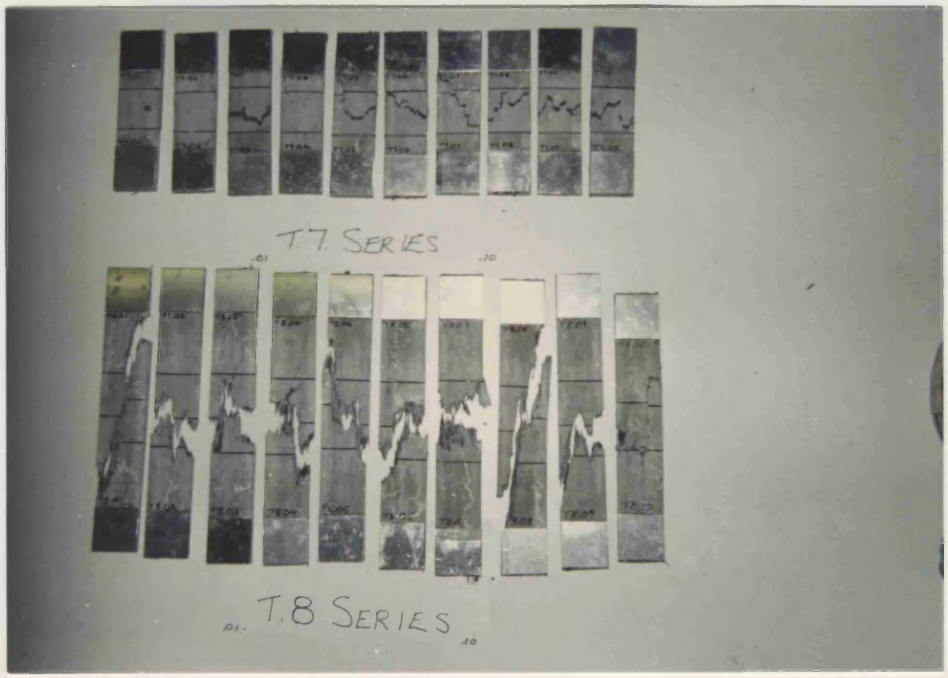
Photograph No. 02

Samples from the T.3 and T.4 Series. Note the different end plate arrangements of the T.3 Series and the two necked samples.

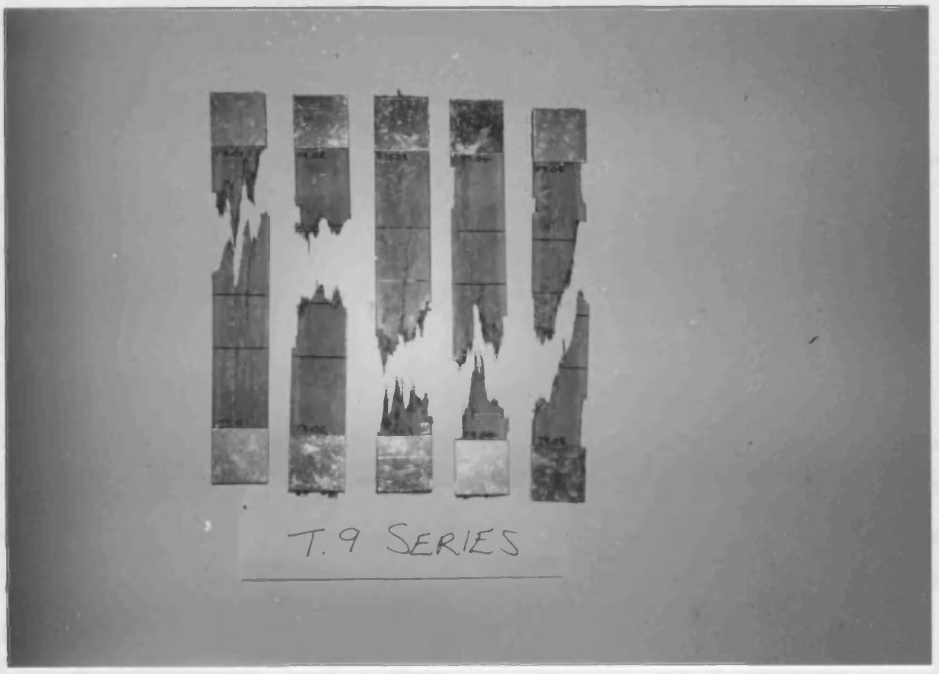


Photograph No. 03

Samples from the T.5 and T.6 Series. Note the shorter, thicker samples of the T.6 Series.



Photograph No. 04 Samples from the T.7 and T.8 Series. The T.7 Series utilised the alternative PVA resin which was less water soluble.



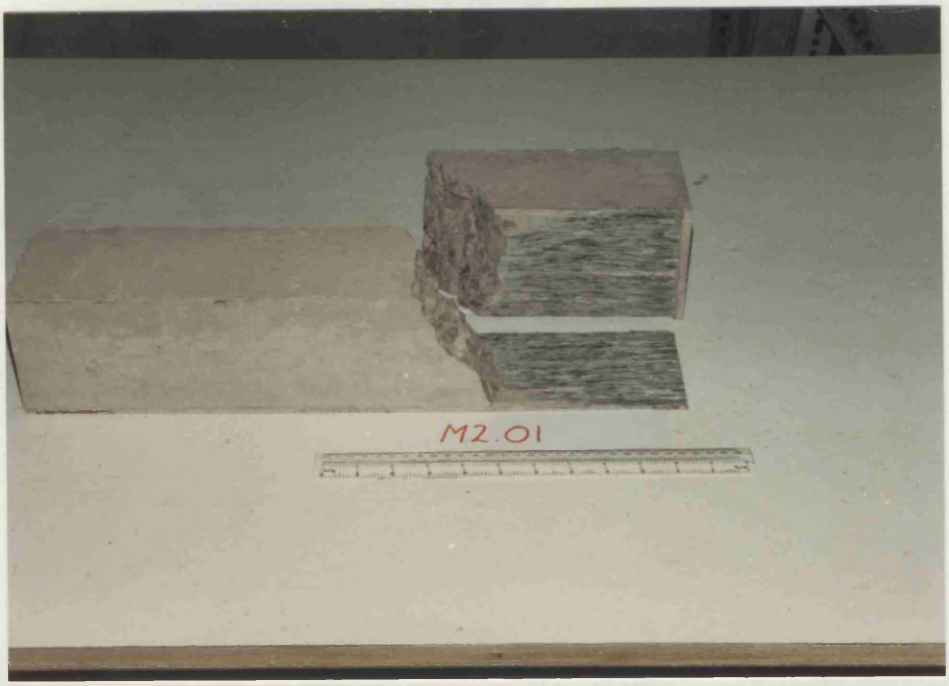
Photograph No. 05 Samples from the T.9 Series which were tested at age 41 days.

A9.3 Flexural Tests : M Series.

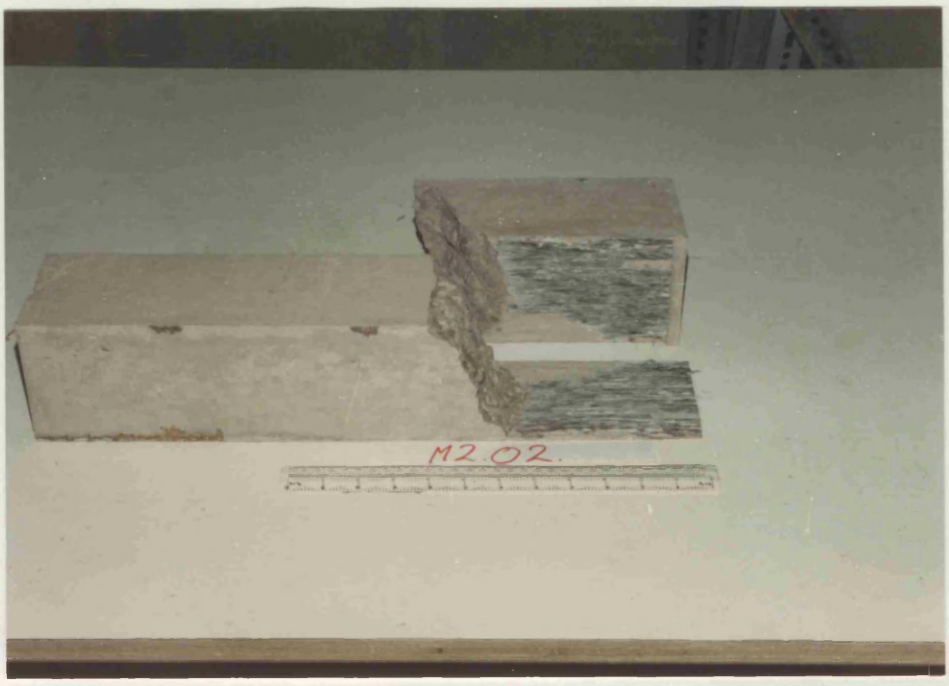
This section includes photographs of the samples of the M.2 Series of flexural tests which were carried out on concrete beams reinforced by CFRC plates on their underside.

The tests are described in detail in Chapter Eight.

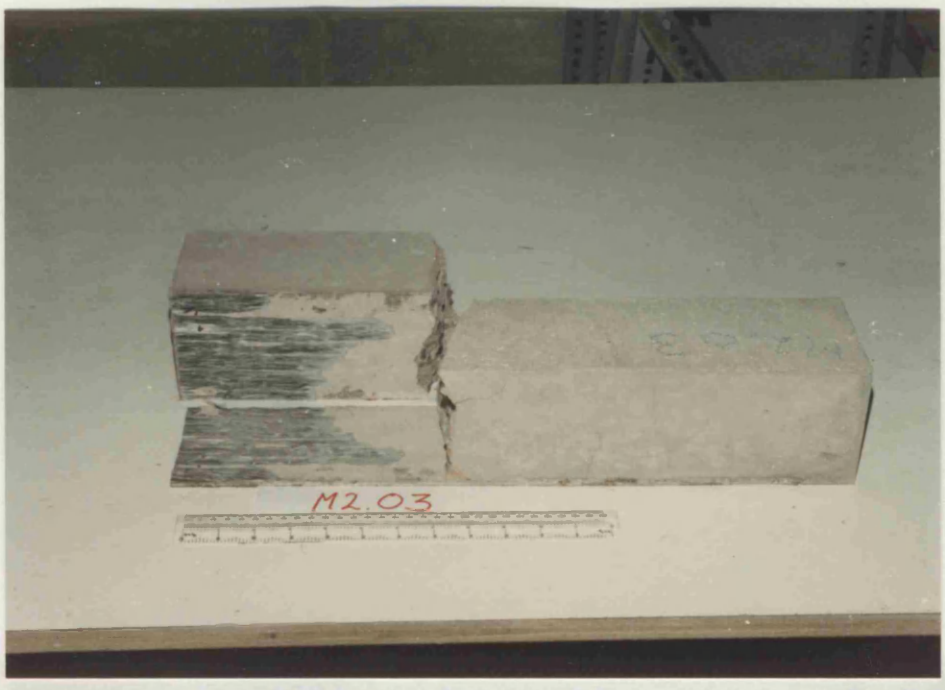
It can be seen from photographs No's 13 and 14 that the surface of the carbon fibre reinforced cement plates were relatively undamaged. This would appear to indicate that in these cases the bond between the plates and the concrete had been relatively poor.



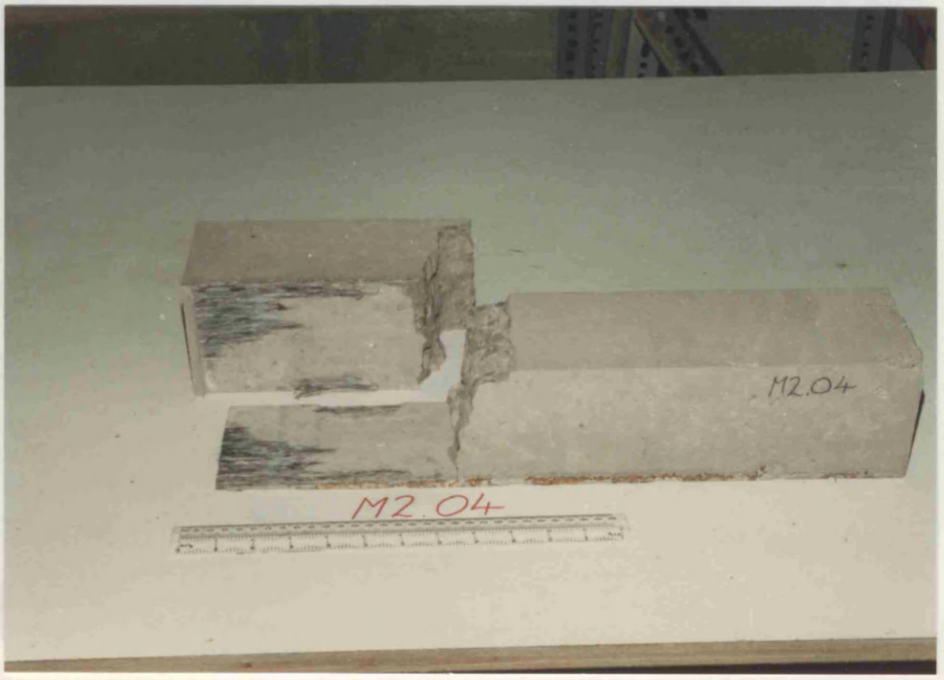
Photograph No. 06 Sample M2.01.



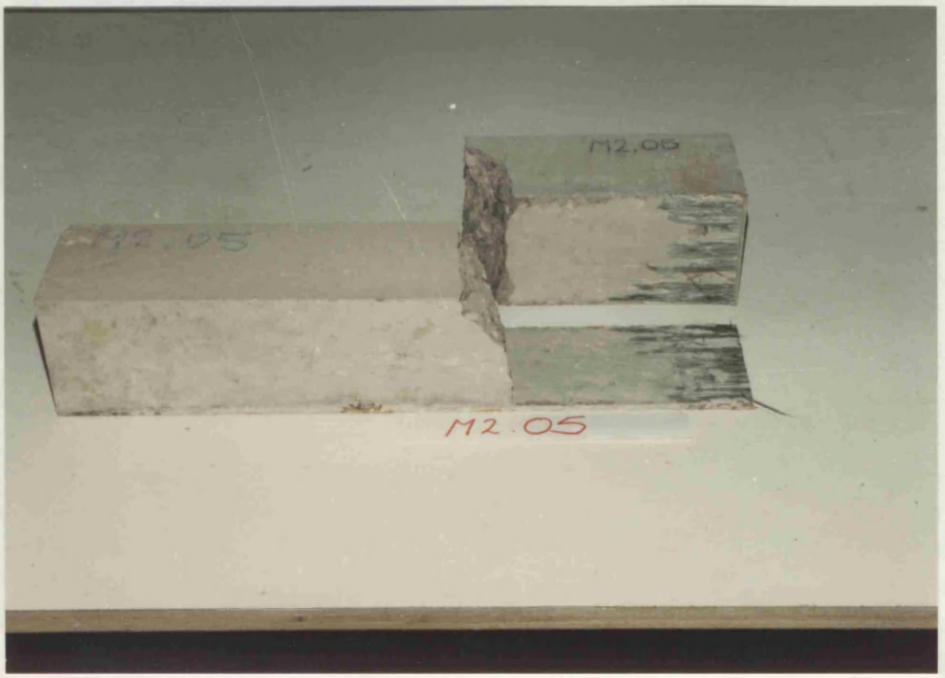
Photograph No. 07 Sample M2.02



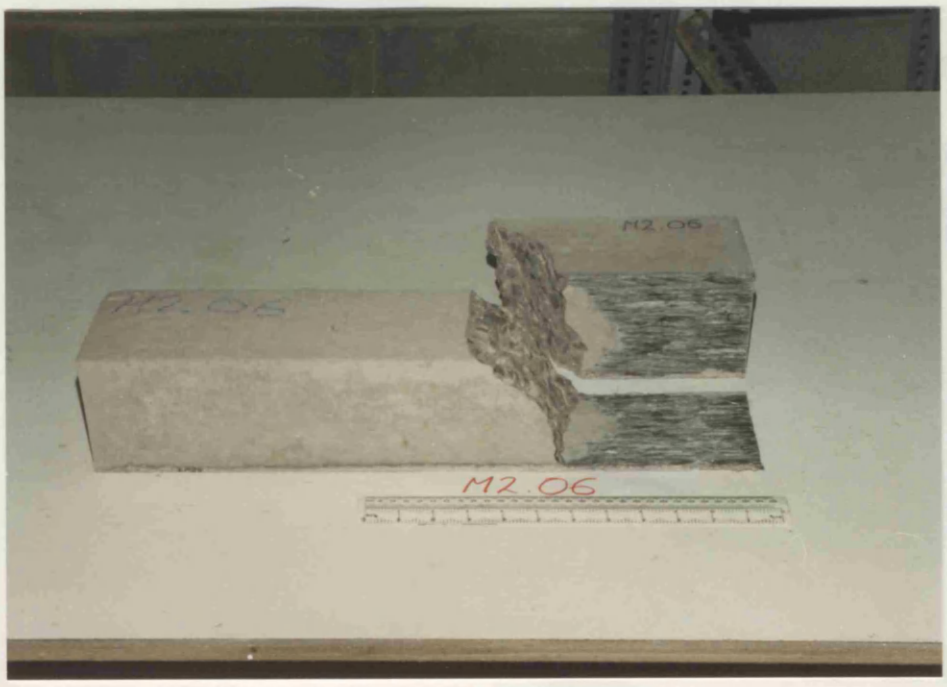
Photograph No. 08 Sample M2.03



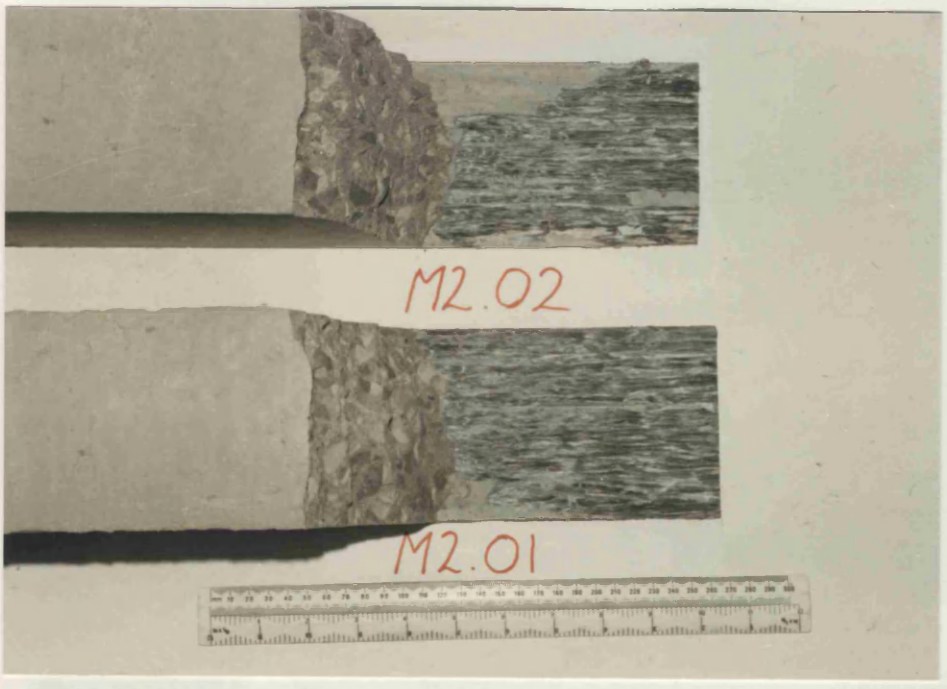
Photograph No. 09 Sample M2.04



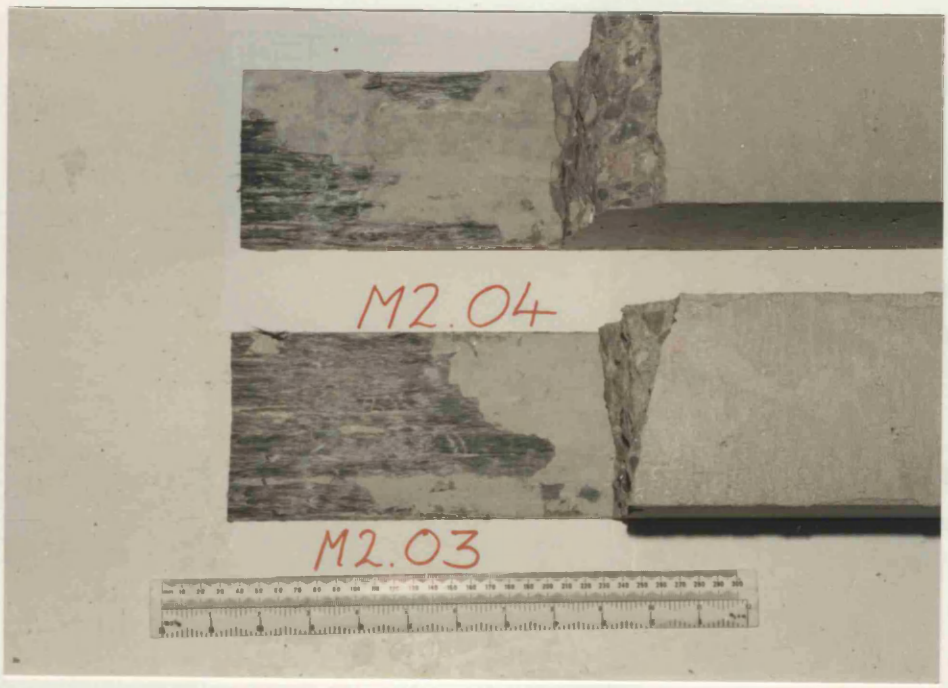
Photograph No. 10 Sample M2.05



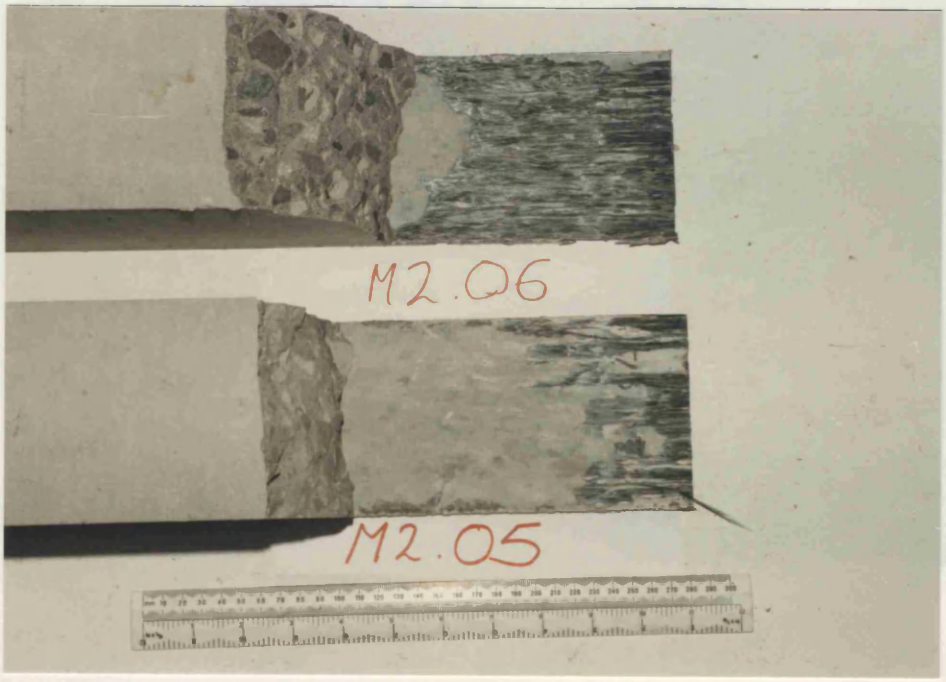
Photograph No. 11 Sample M2.06



Photograph No. 12 Samples M2.01 and M2.02 showing surface of CFRC plate after failure.



Photograph No. 13 Samples M2.03 and M2.04 showing surface of CFRC plate after failure.

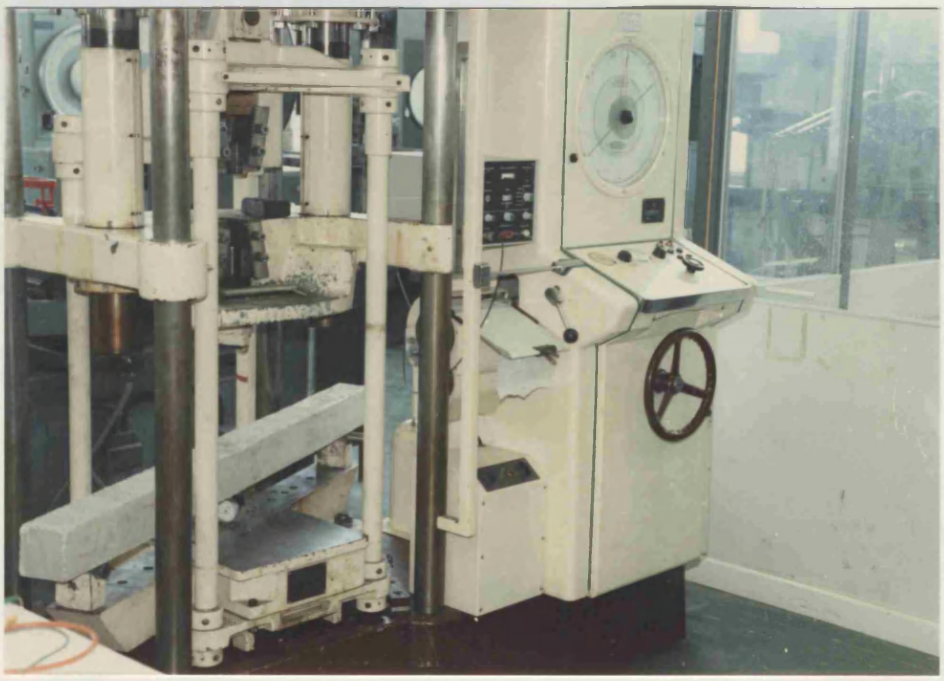


Photograph No. 14 Samples M2.05 and M2.06 showing surface of CFRC plate after failure.

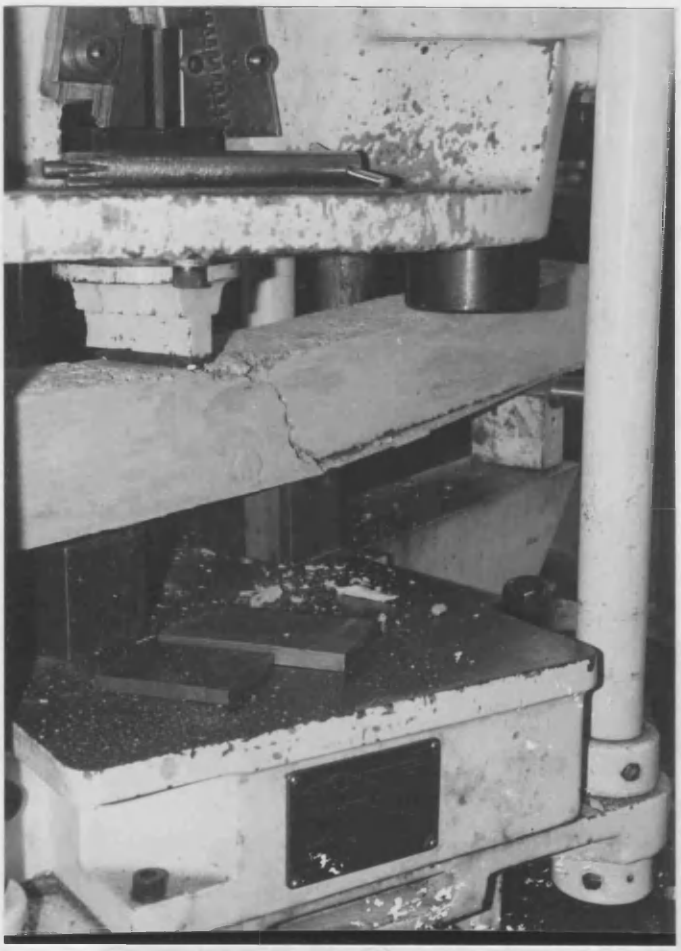
A9.4 Flexural Tests : L Series.

This section includes two photographs of an L Series beam under test. The beams were reinforced by means of carbon fibre reinforced cement plates on their underside.

Photograph No. 16 shows a typical failure mode where the CRFC plate has delaminated from the underside of the concrete section. A tension crack has spread upwards through the concrete from the interface to the point of application of the load.



Photograph No 15 Sample L1.07 in position prior to testing.



Photograph No. 16

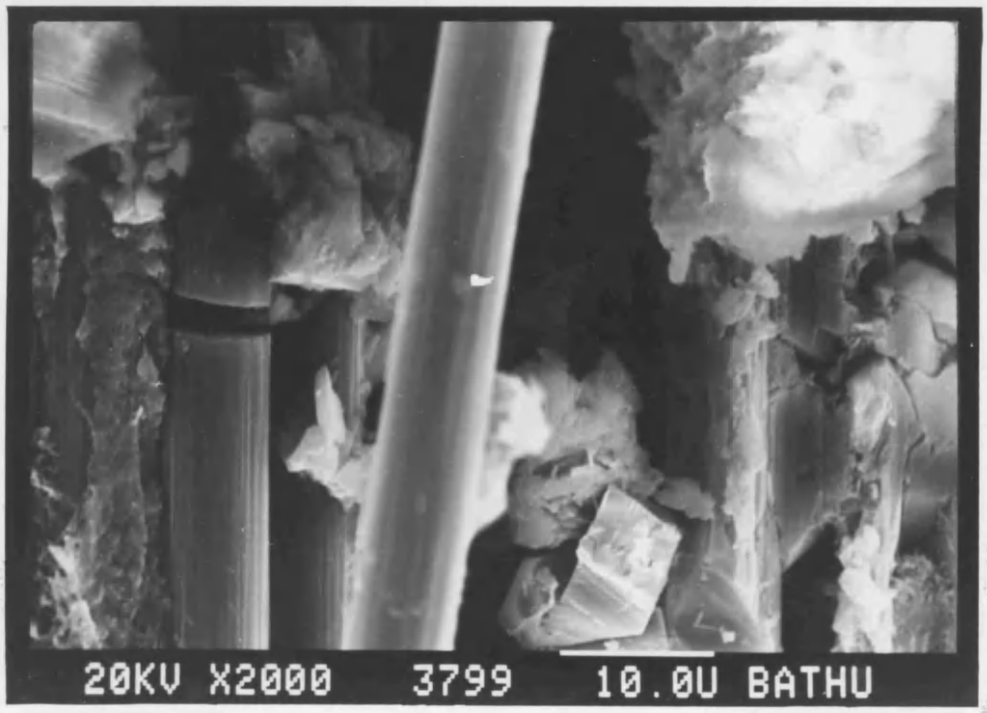
Sample L1.07 after failure due to delamination of the CFRC plate from the underside.

A9.5 S.E.M Photographs.

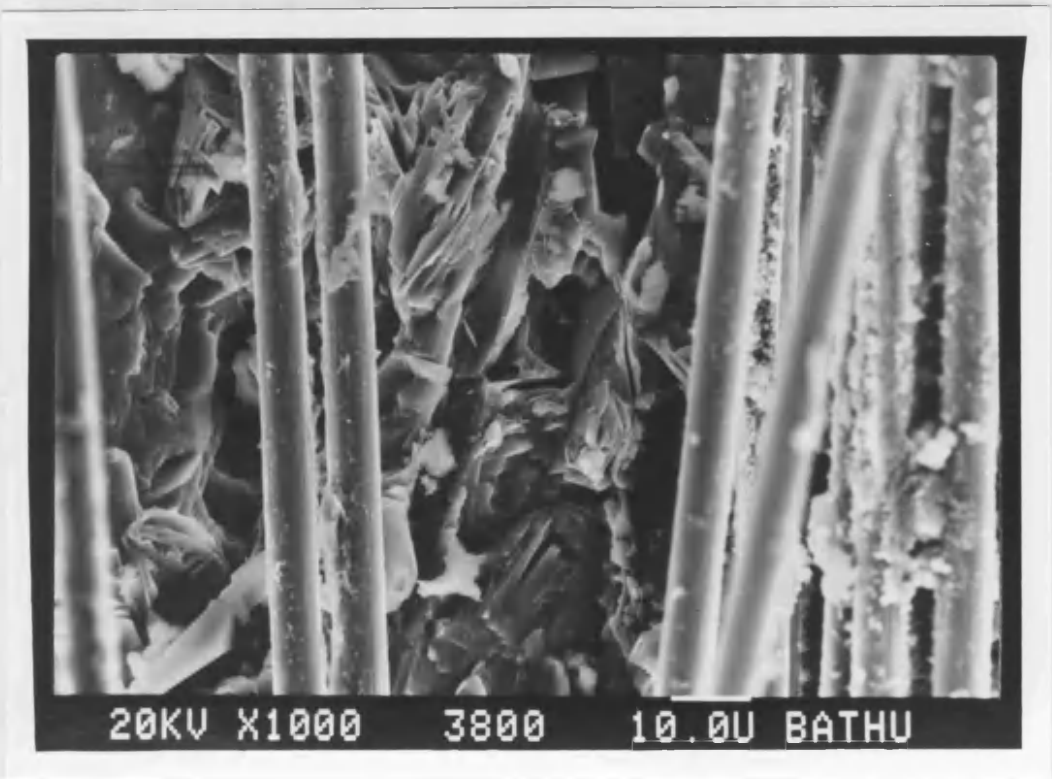
This section contains photographs which were taken using a Scanning Electron Microscope.

All of the photographs are of carbon fibre reinforced cement samples in which the fibre reinforcement was in the form of PVA prepreg.

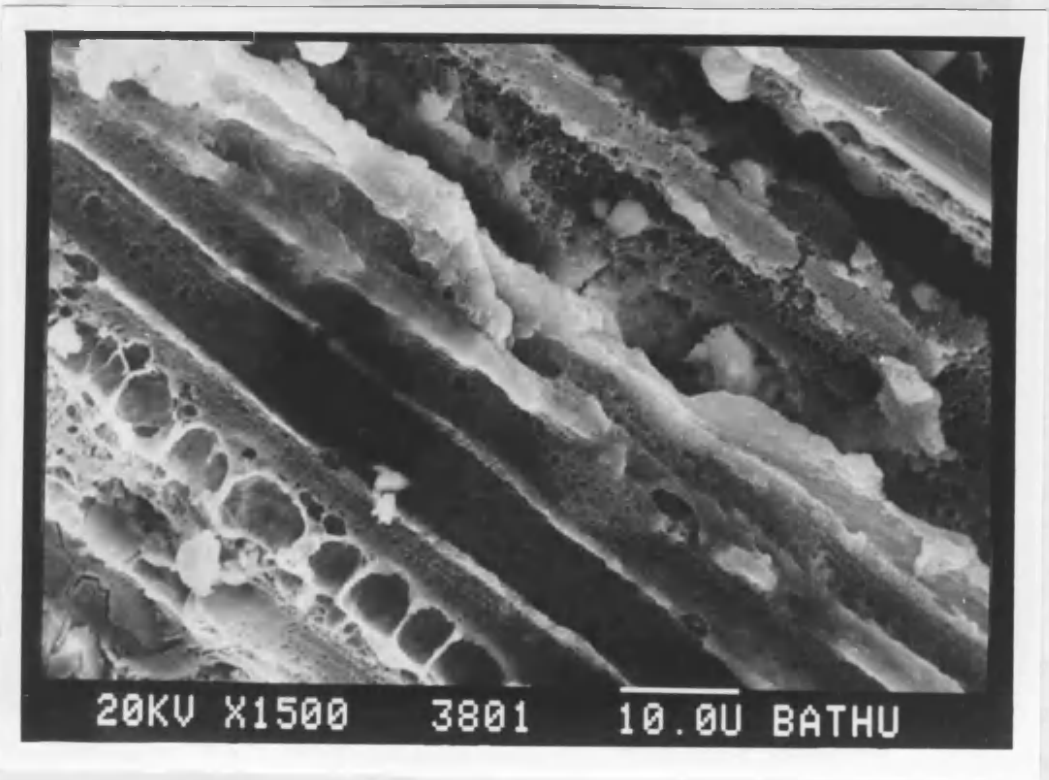
The samples which were used for the photographs were taken from the CFRC plates used as reinforcement for the M.2 Series of flexural tests after failure.



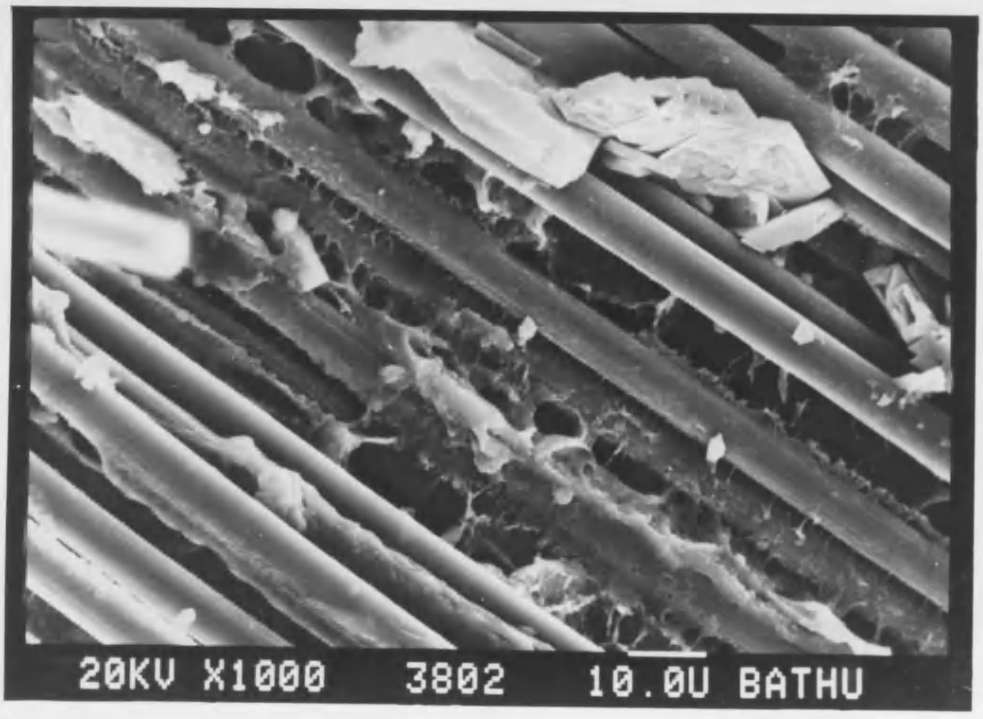
Photograph No. 17 To the left of the frame is a fibre which appears to have failed in tension, to the right of the frame can be seen the impression left in the cement matrix by a fibre which is now missing.



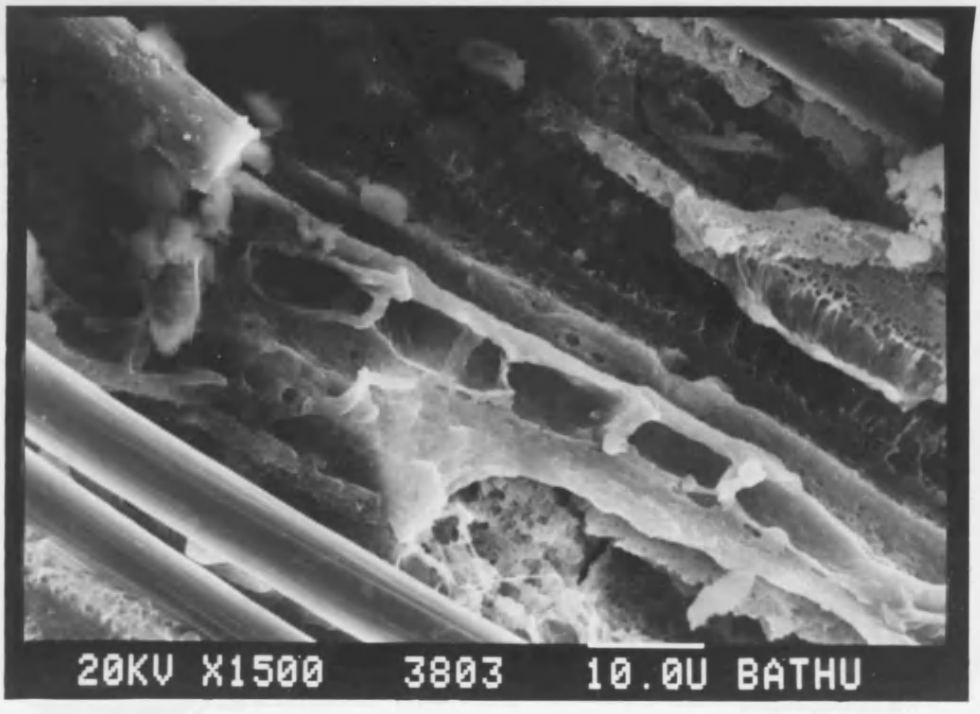
Photograph No. 18 In the foreground are carbon fibres, apparently with fragments of matrix material still attached. In the background can be seen the cement matrix which contains the impression of a missing fibre.



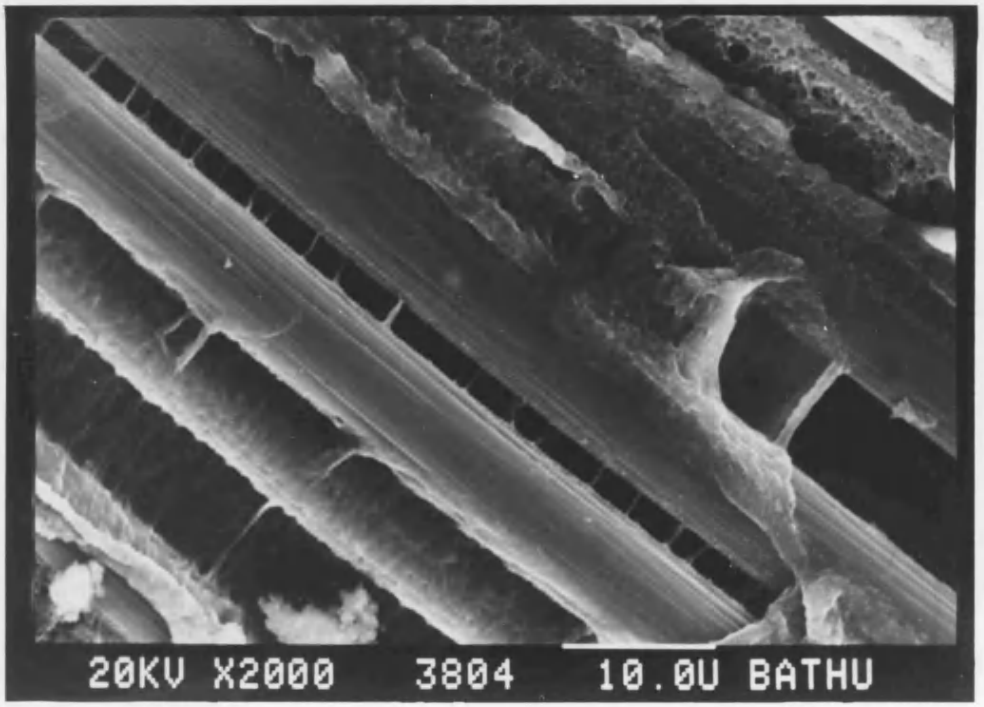
Photograph No.19 This photograph appears to show the impressions of missing fibres in the PVA matrix of the prepreg.



Photograph No. 20 In the centre of the frame are fibres apparently coated in PVA resin, to the top right can be seen fragments of the cement matrix.



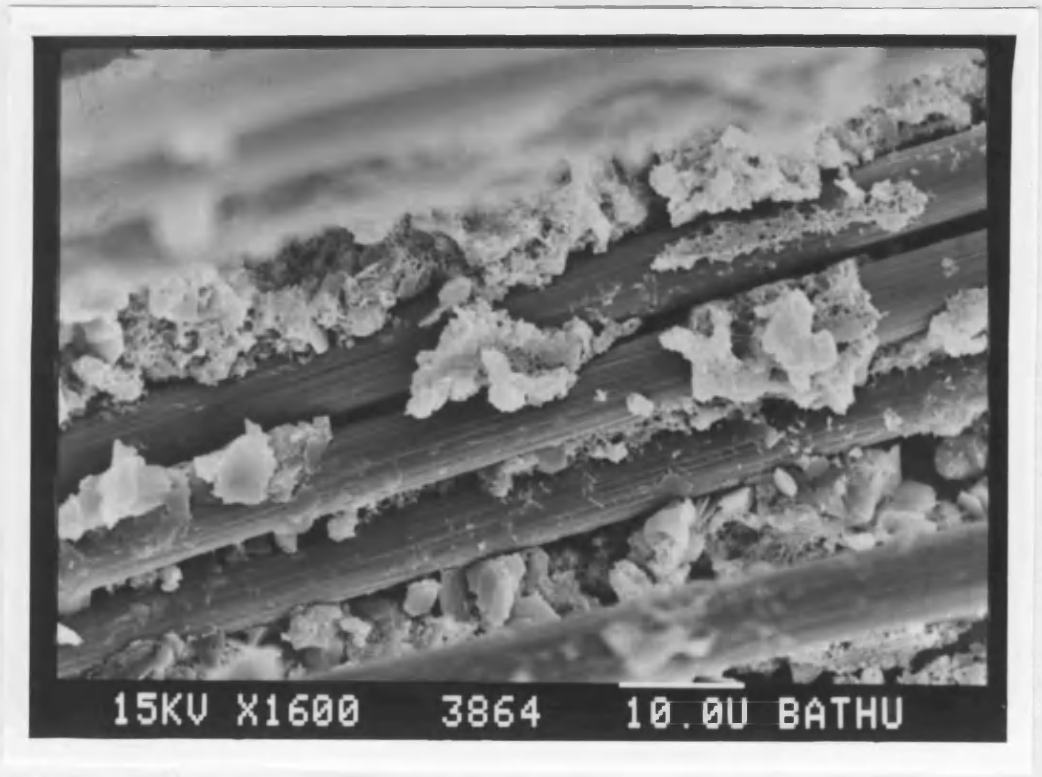
Photograph No. 21 To the top left of the frame can be seen the end of a fibre apparently broken in tension. In the centre of the frame can be seen PVA resin which contains the impression of a missing fibre. Note also the relatively large voids which exist in the matrix.



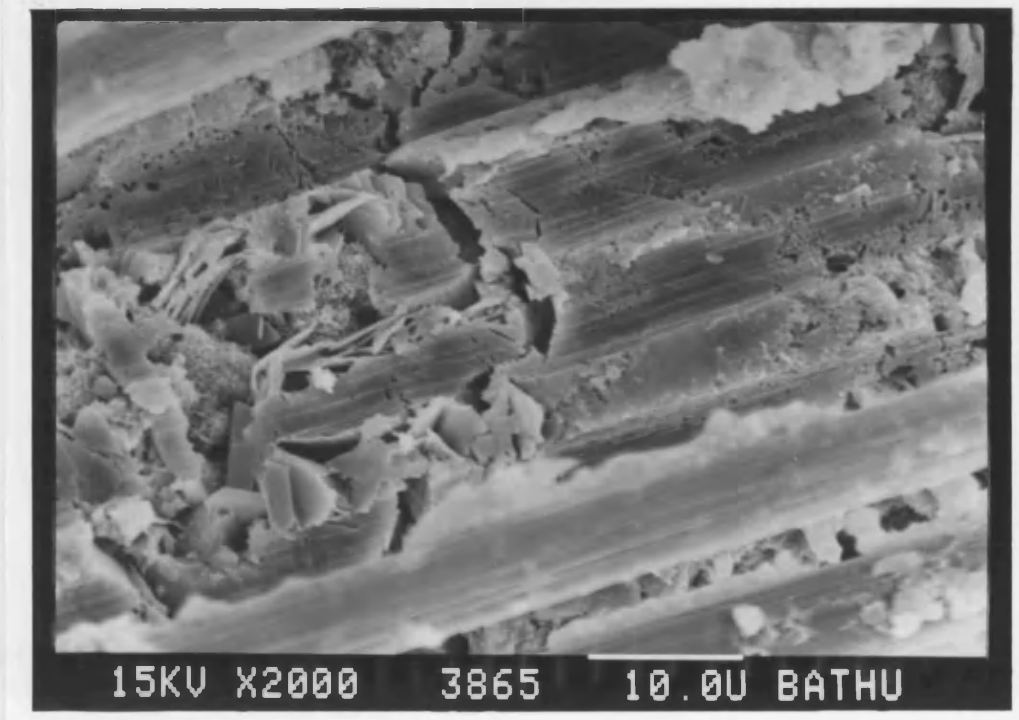
Photograph No. 22 Carbon fibres, partially or fully coated in PVA resin.

Photograph No. 23 In the foreground is a carbon fibre, apparently with fragments of matrix attached. In the background there appears to be large voids in the matrix.

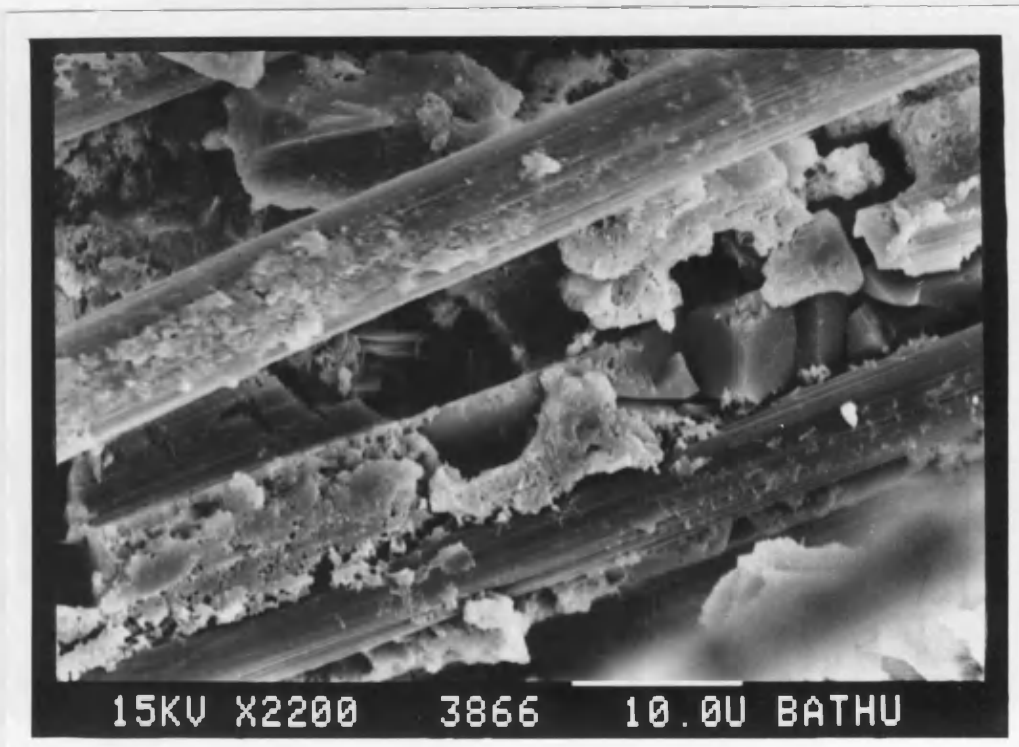
Photograph No. 24 A single carbon fibre with fragments of cement matrix attached.



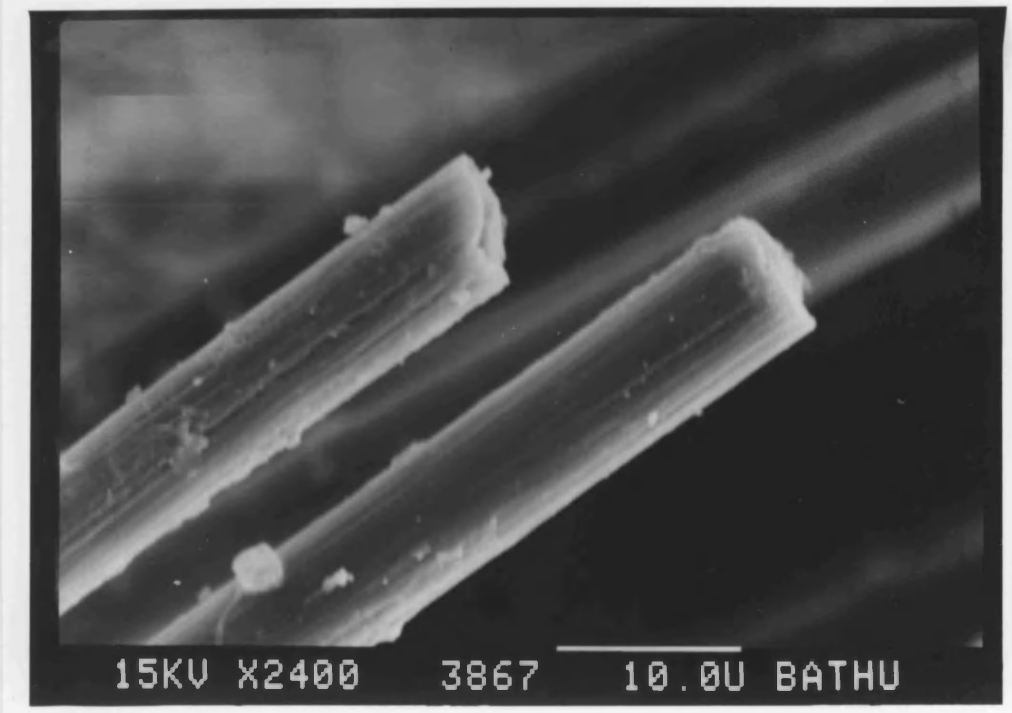
Photograph No. 25 Carbon fibres in cement matrix.



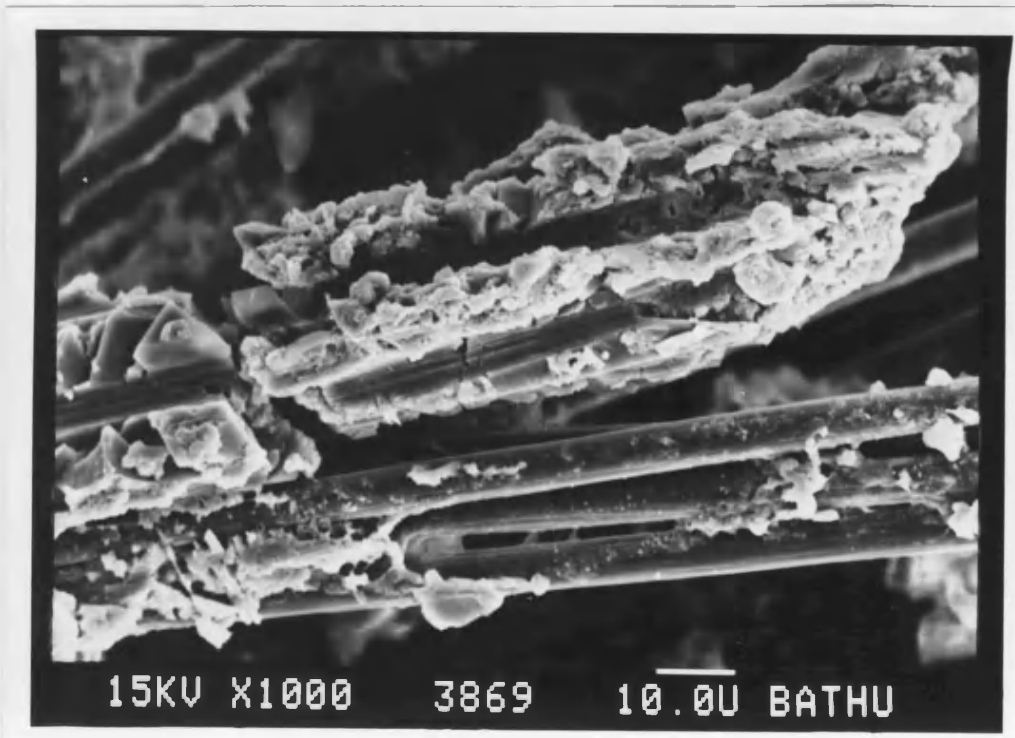
Photograph No 26 The impressions of carbon fibres in a fractured cement matrix.



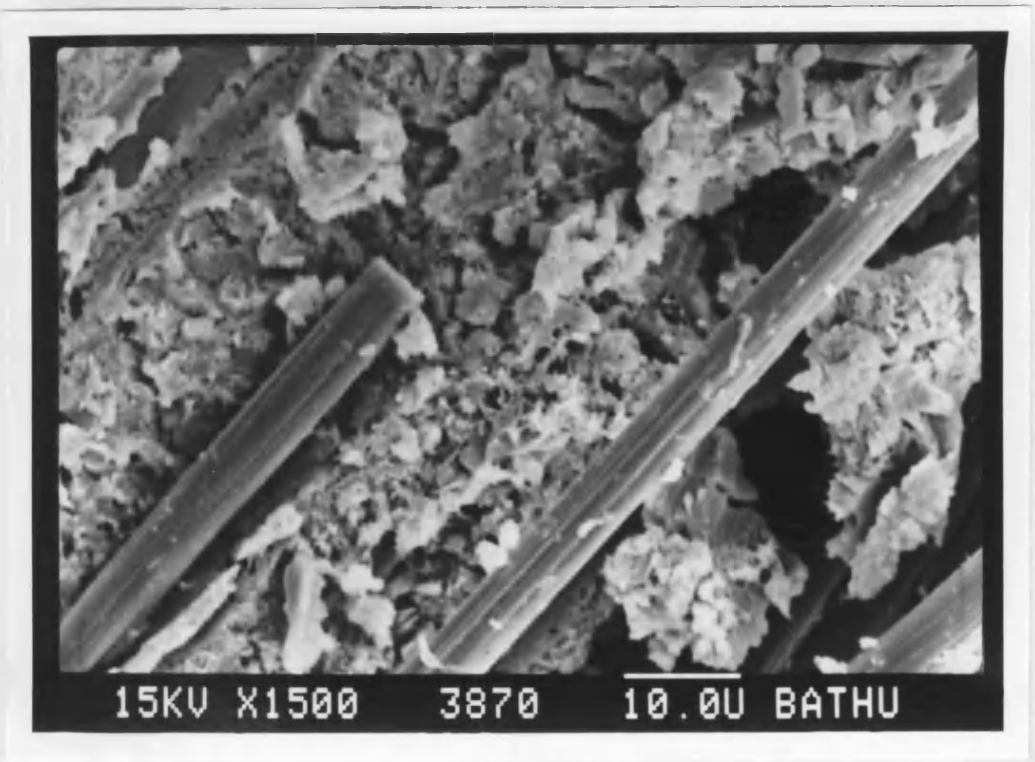
Photograph No. 27 Carbon fibres among crystals of cement matrix containing many voids.



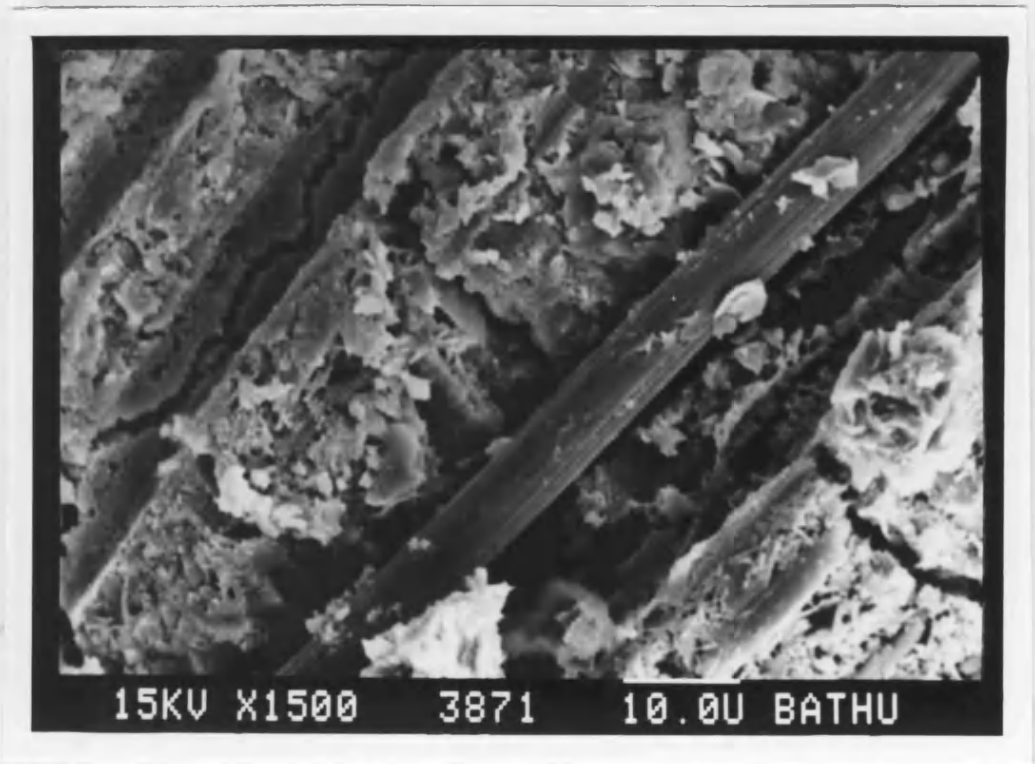
Photograph No.28 Two carbon fibres which have apparently failed in tension.



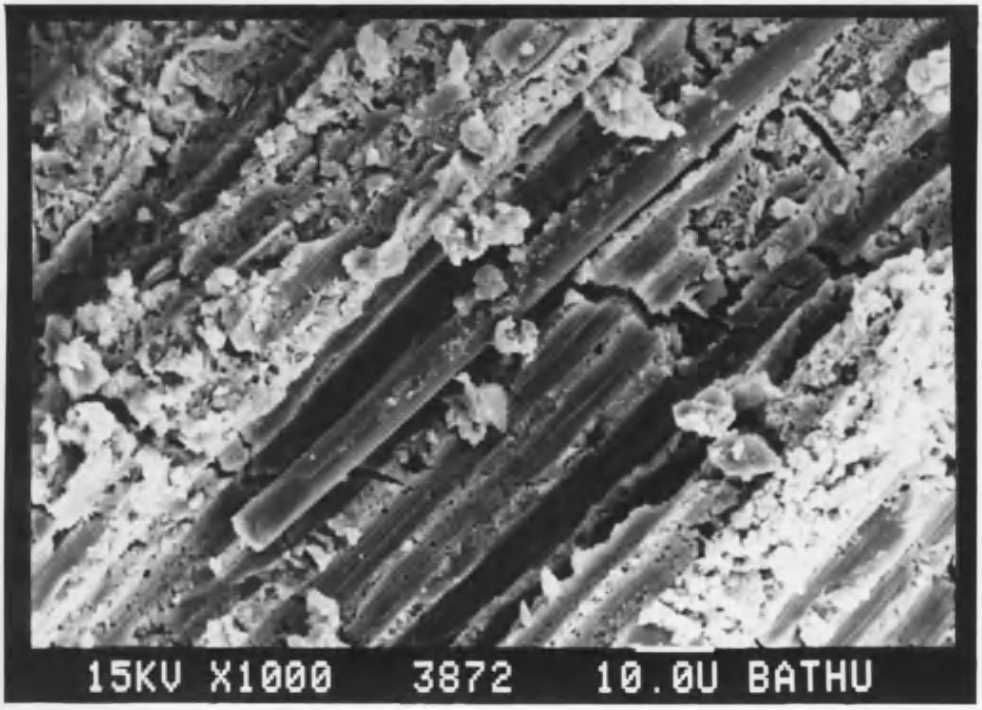
Photograph No. 29 Carbon fibres and pieces of cement matrix.



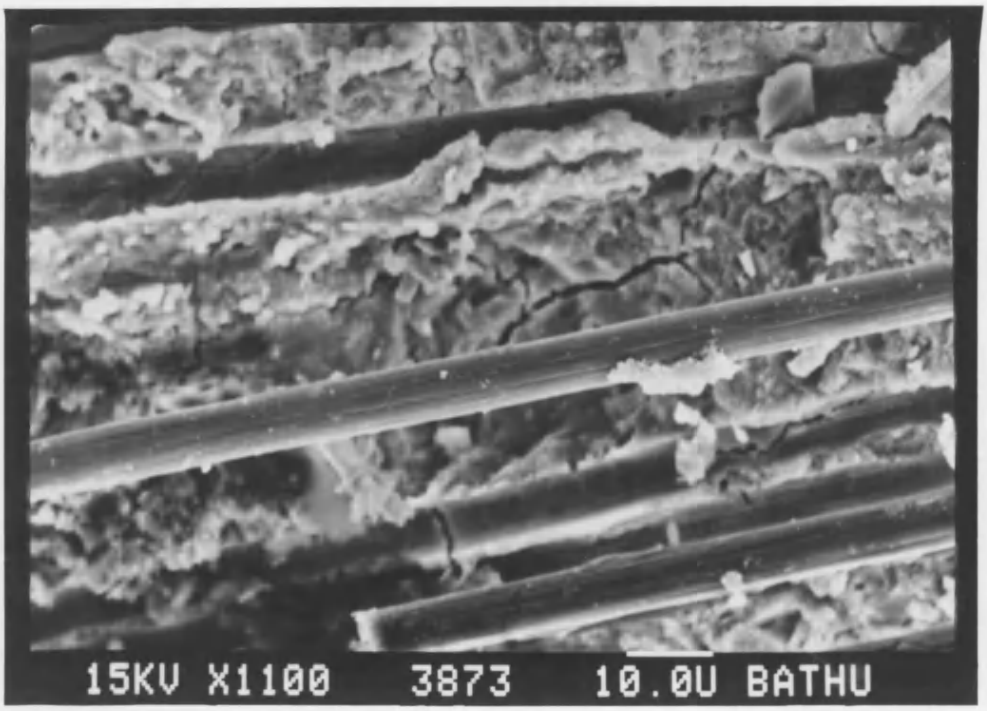
Photograph No. 30 In the centre of the frame is a carbon fibre which has apparently failed in tension, note the many voids in the cement matrix.



Photograph No. 31 To the top left of the frame is the impression of a missing fibre in the cement matrix. In the centre of the frame is a fibre with small fragments of matrix attached.



Photograph No. 32 In the centre of the frame is a fibre which appears to have failed in tension. Note the many impressions of missing fibres in the fractured cement matrix.



Photograph No. 33 In the foreground is a fibre with small fragments of cement matrix attached. In the lower background is a fractured fibre and possibly either the fractured cement matrix containing the impression of a missing fibre or another broken fibre still in-situ.

APPENDIX TEN

Typical Load/Extension Curves

A10.1 Introduction.

During the course of the research many tensile tests were carried out both on samples of carbon fibre/PVA prepreg and on samples of cement plates which had been reinforced using prepreg.

The Instron 1122 test machine which was used for the tensile tests on samples of PVA prepreg automatically plotted graphs of applied load against cross-head displacement.

The Instron 1195 test machine used for the tests on the samples of CFRC plotted graphs of applied load against gauge length extension. A 50mm gauge length in the centre of the sample was used in all cases and the extension was measured using a Wallace optical extensometer.

Because of the large number of tests which were carried out it is not practical to include all of the graphs which were obtained. Consequently typical examples only are included. Full details of the relevant test series can be found in the main text. In particular, the tests on the PVA prepreg are described in Appendix Seven, the tests on the samples of CFRC are described in Appendix Eight.

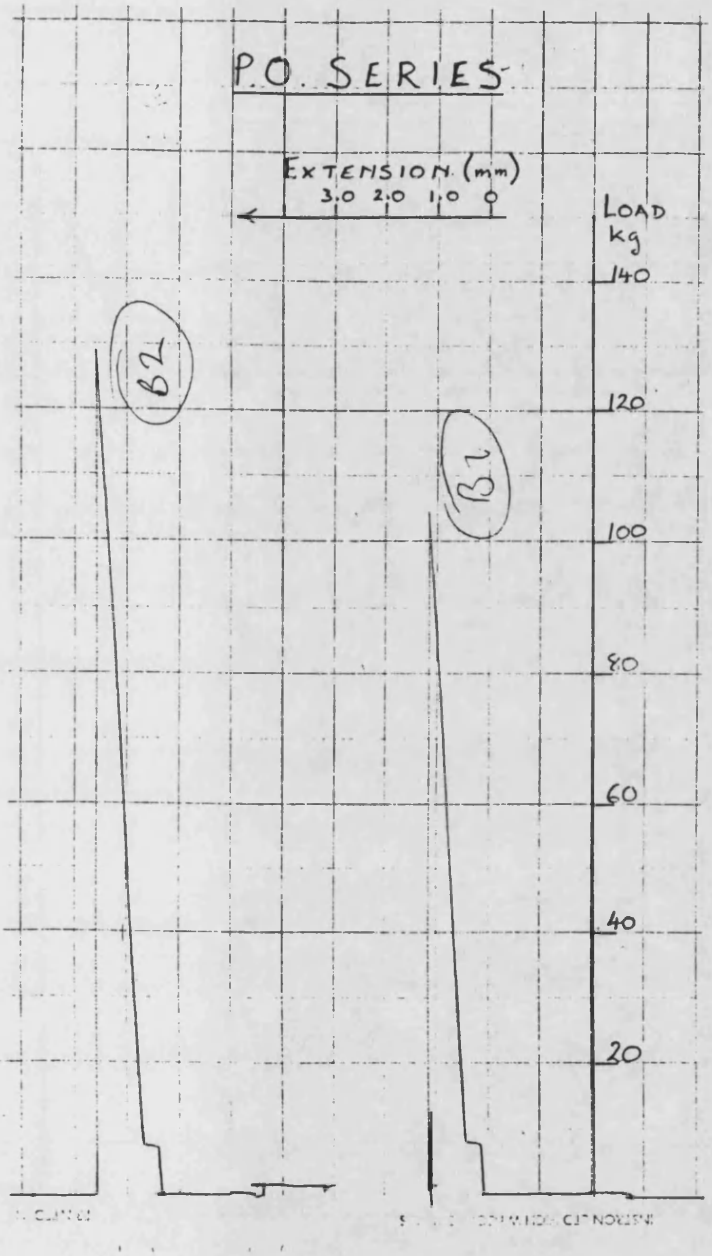


Fig. A10.1 Tensile Tests : PVA Prepreg P.0 Series. Note the step in the graph where Multiple Fracture of the matrix is taking place.

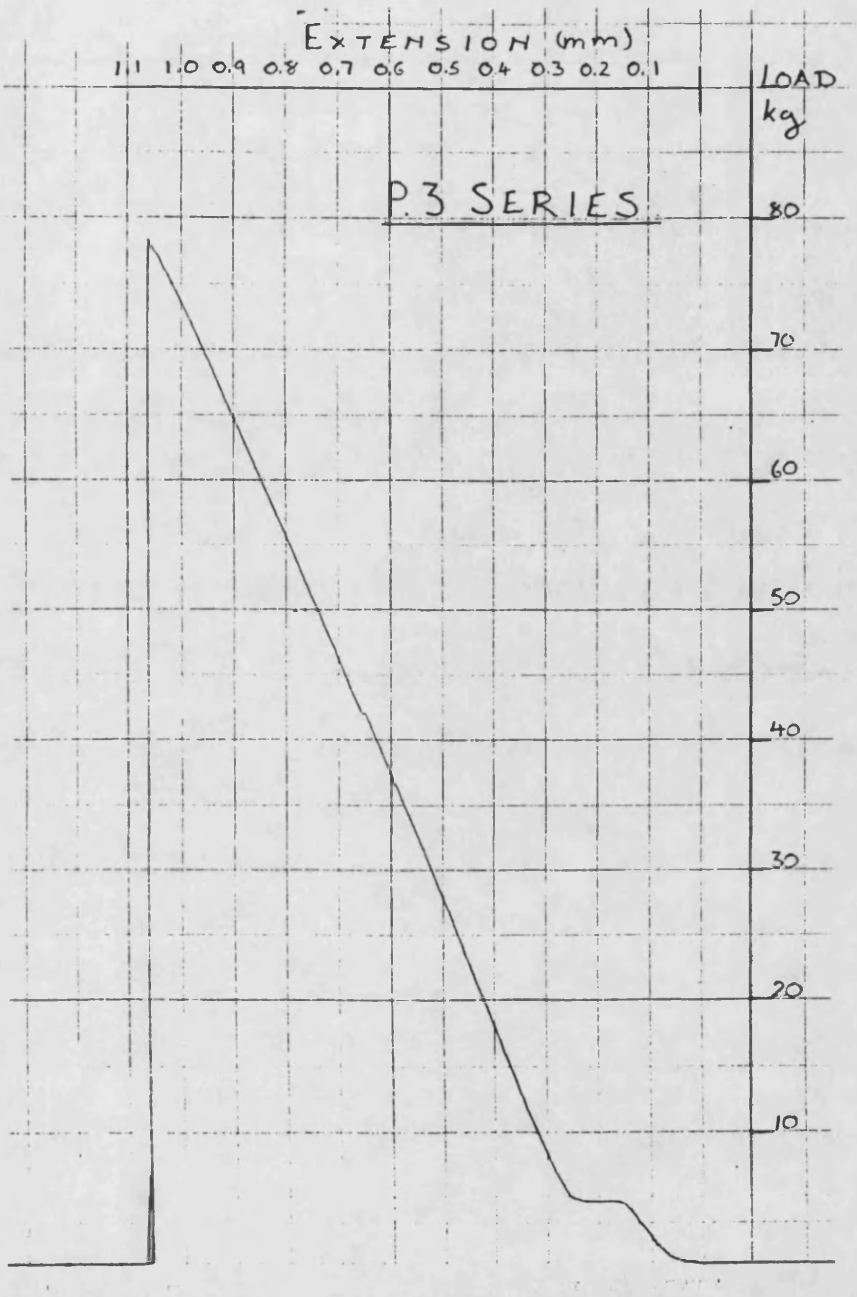


Fig. A10.2 Tensile Tests : PVA Prepreg P.3 Series.

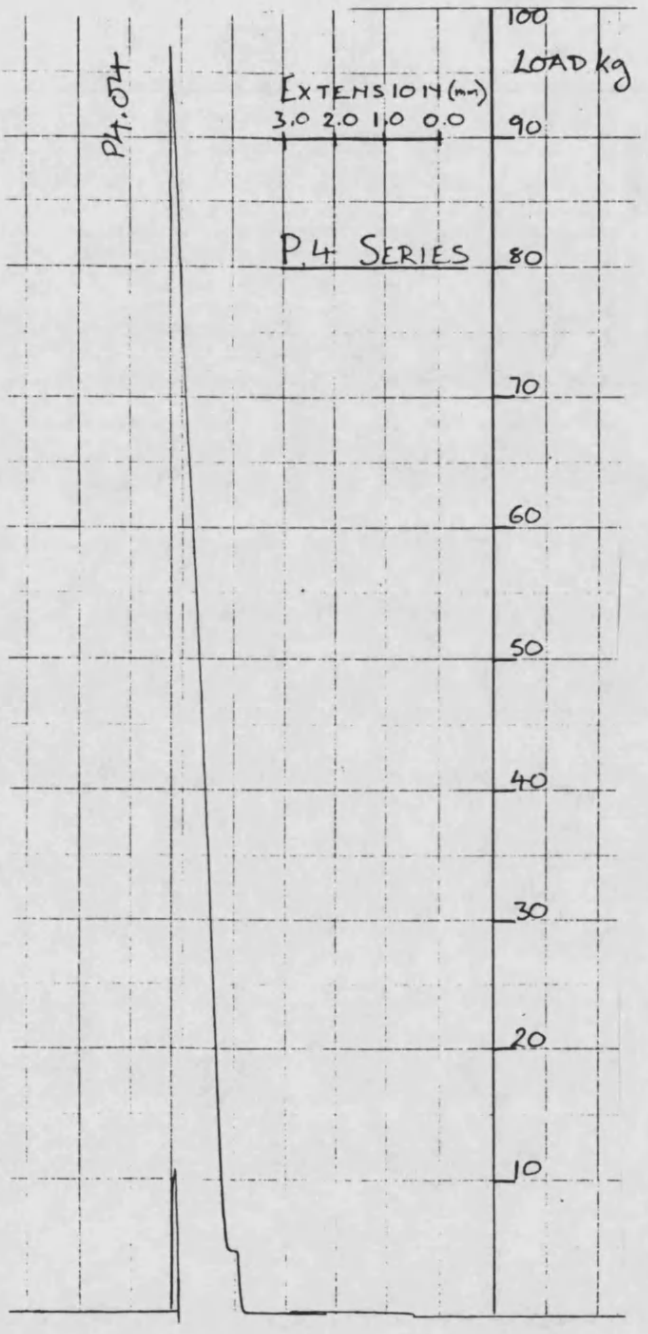


Fig. A10.3 Tensile Tests : PVA prepreg P.4 Series.

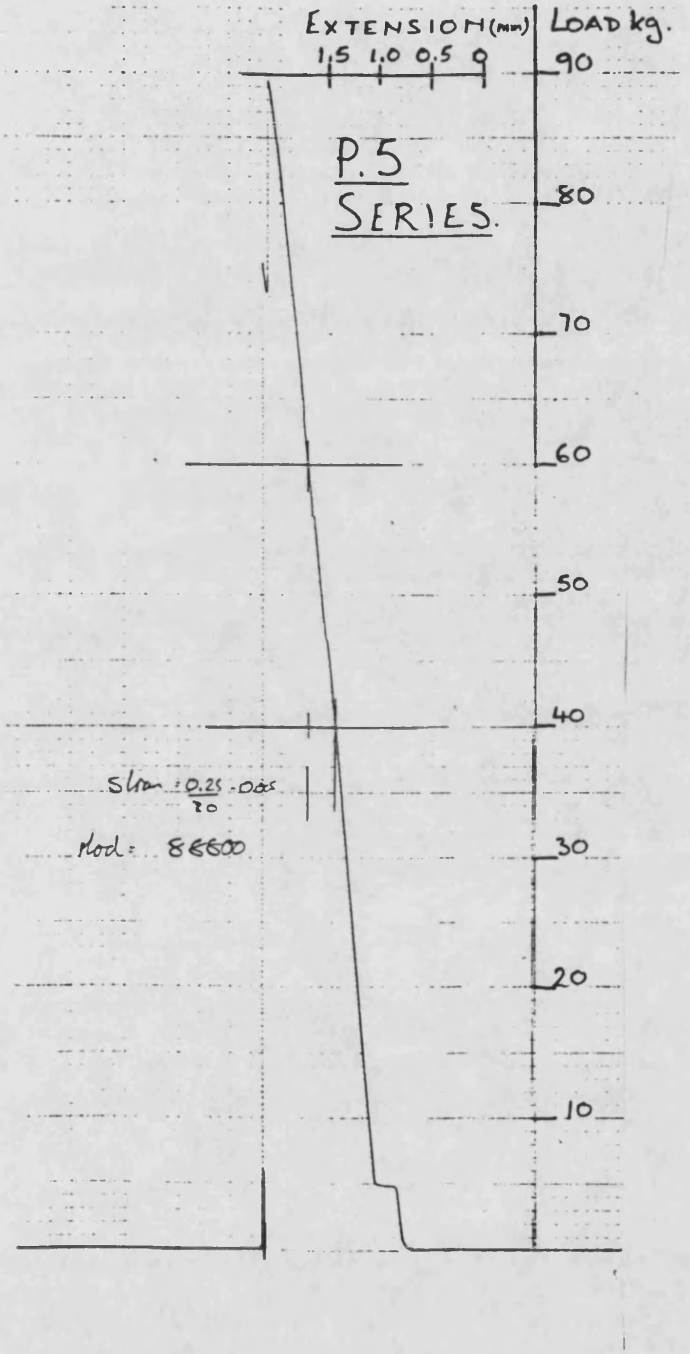


Fig. A10.4 Tensile Tests : PVA Prepreg P.5 Series.

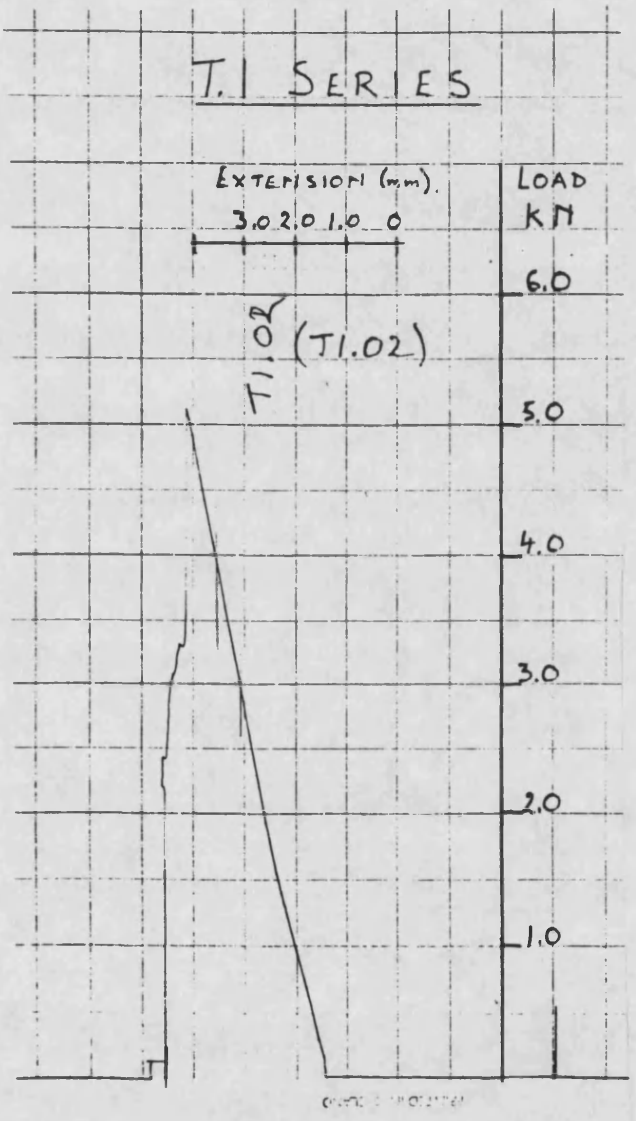


Fig. A10.5 Tensile Tests : CFRC T.1 Series. No PVA added to the cement paste. (V_f = 0.049).

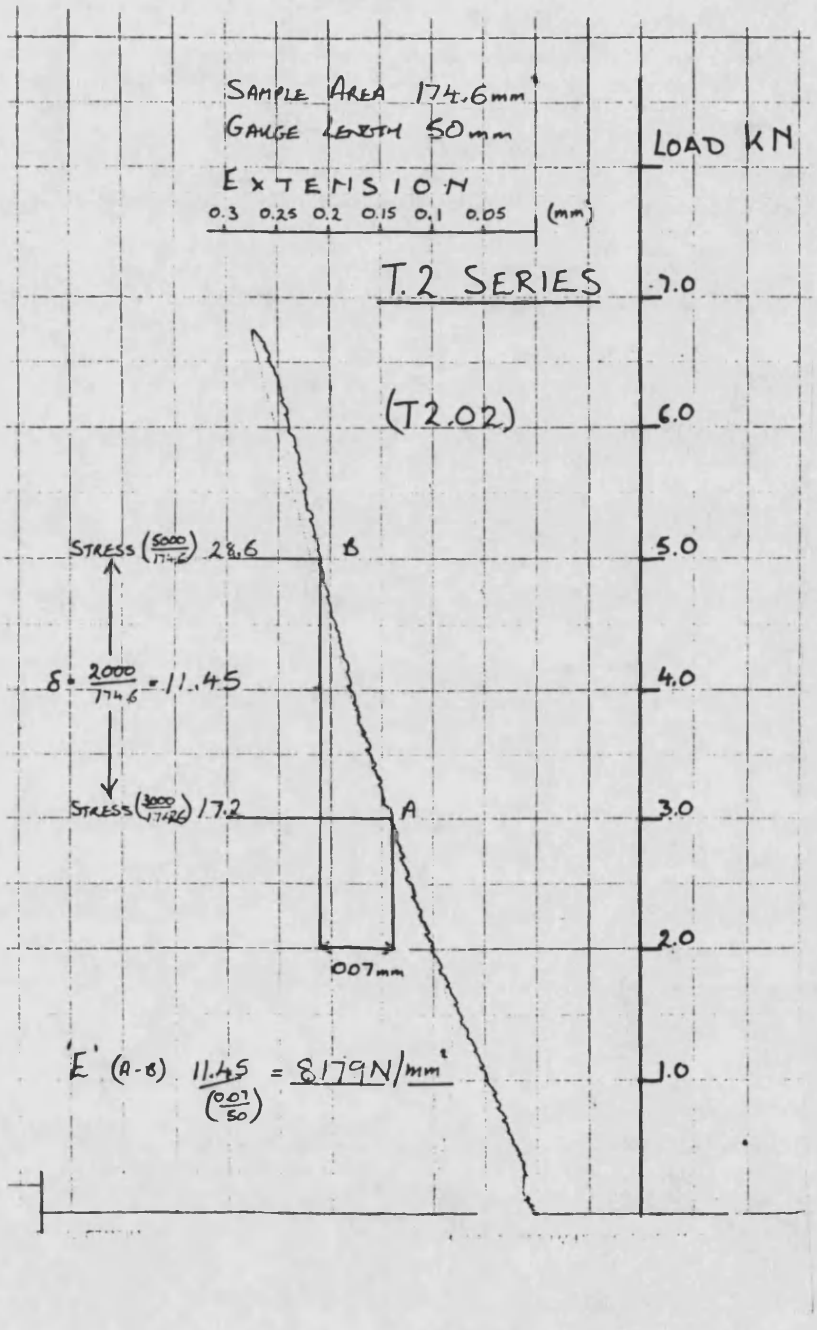


Fig. A10.6 Tensile Tests : CFRC T.2 Series. No PVA added to the cement paste. (V_f = 0.045).

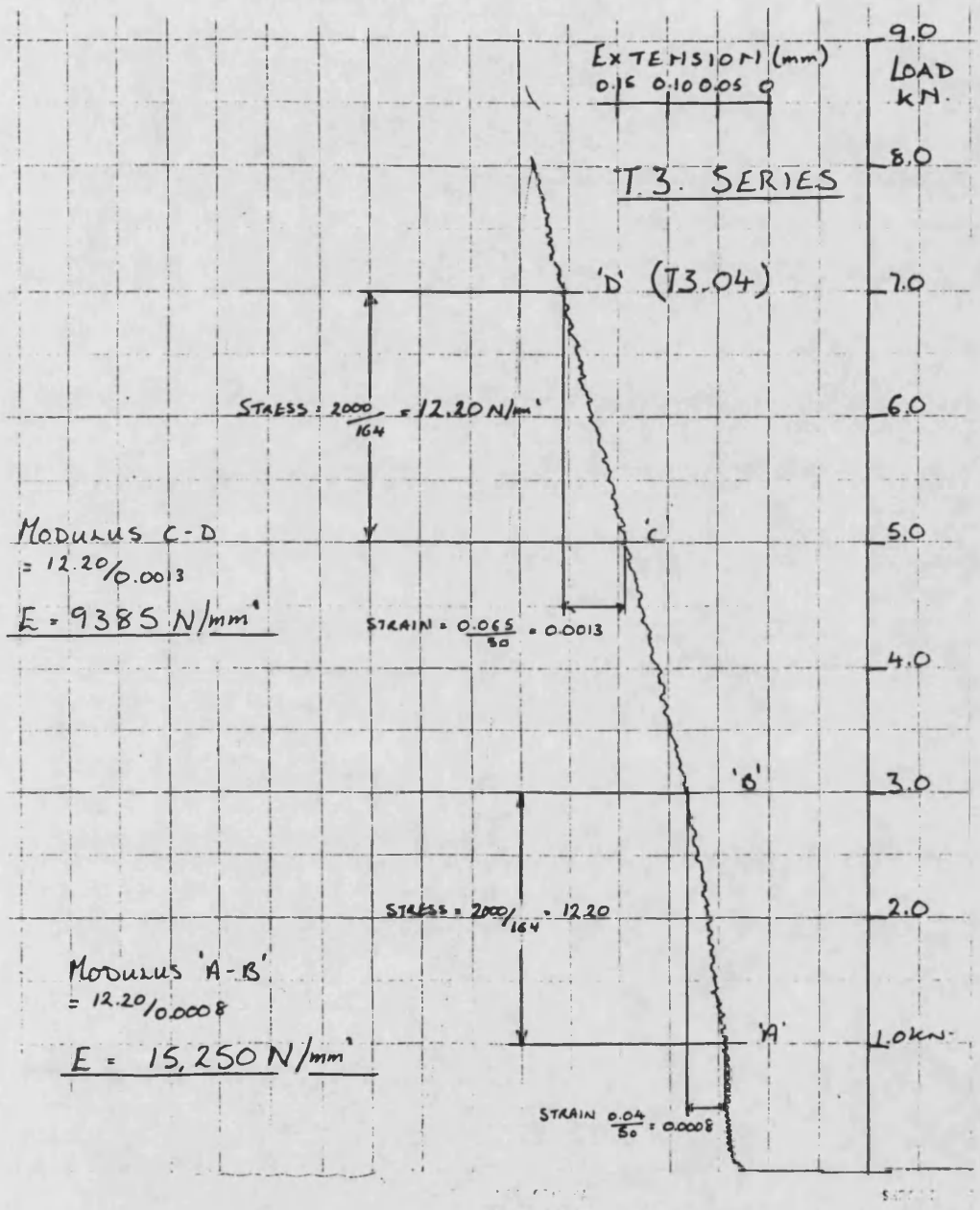


Fig. A10.7 Tensile Tests : CFRC T.3 Series. PVA added to the cement paste, long end plates. (V_f = 0.046).

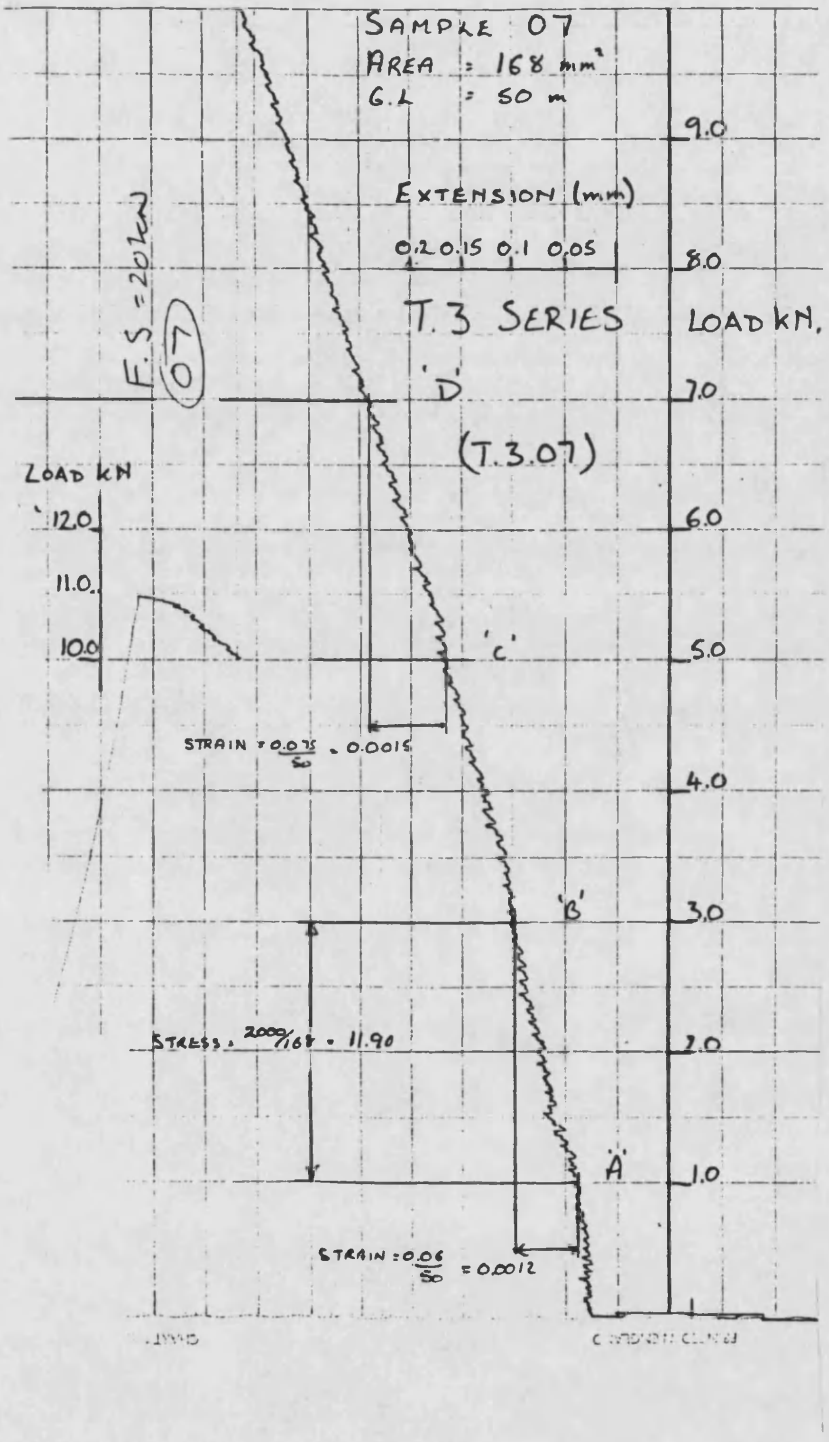


Fig. A10.8 Tensile Tests : CFRC T.3 Series. PVA added to the cement paste, short end plates. (V_f = 0.045).

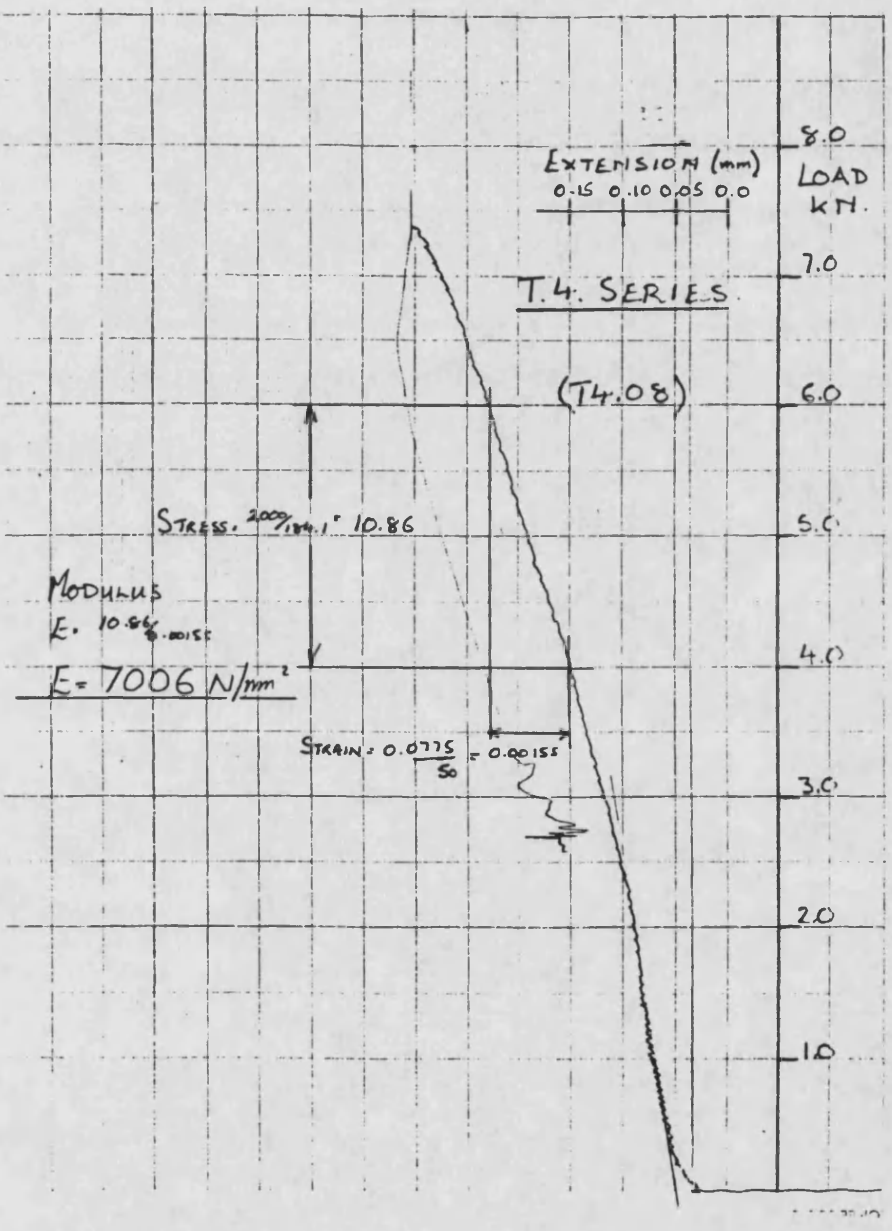


Fig. A10.9 Tensile Tests : CFRC T.4 Series. No PVA added to the cement paste, short end plates. (V_f = 0.043)

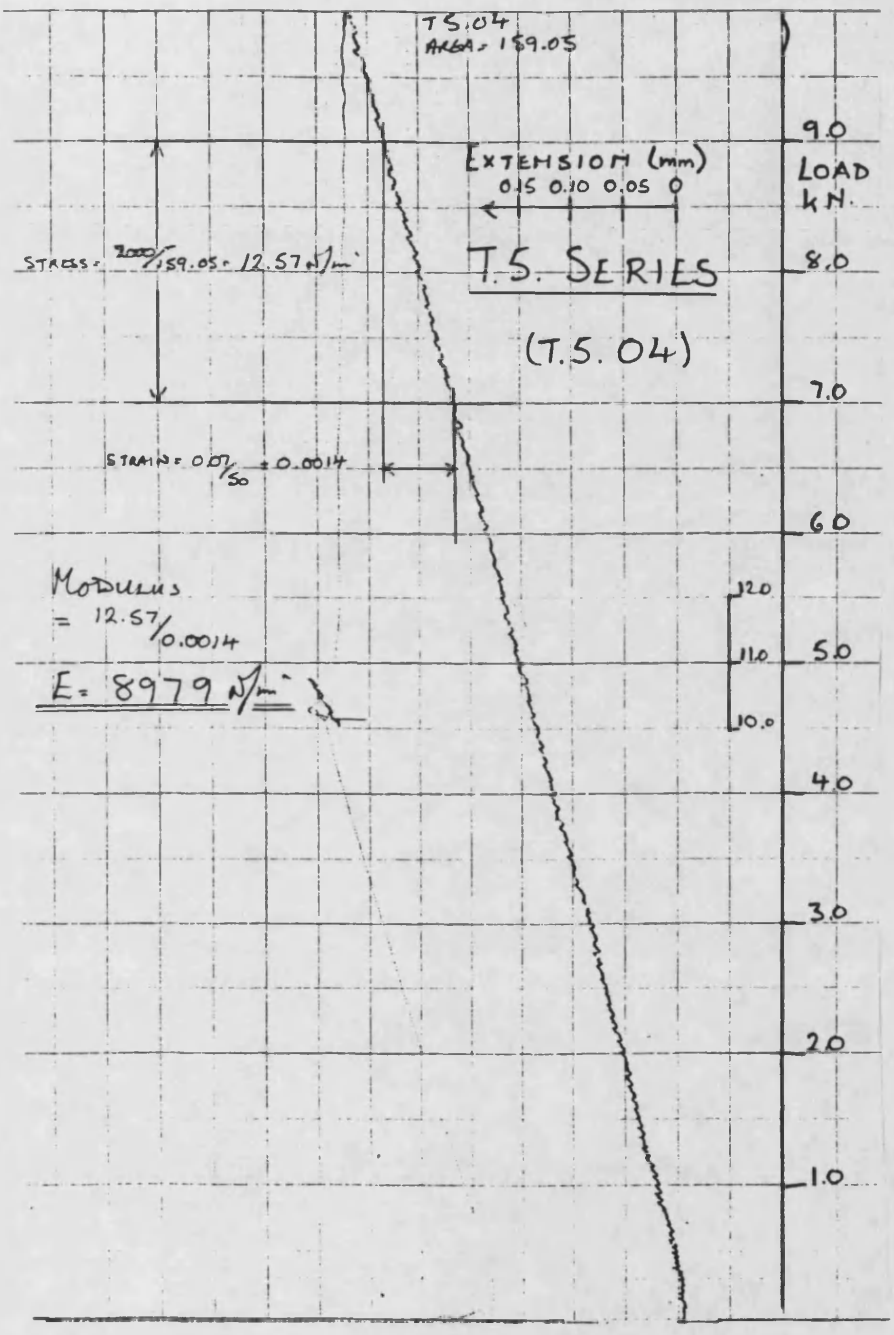


Fig. A10.10 Tensile Tests CRFC T.5 Series, PVA added to the cement paste, short end plates. (V_f = 0.047).

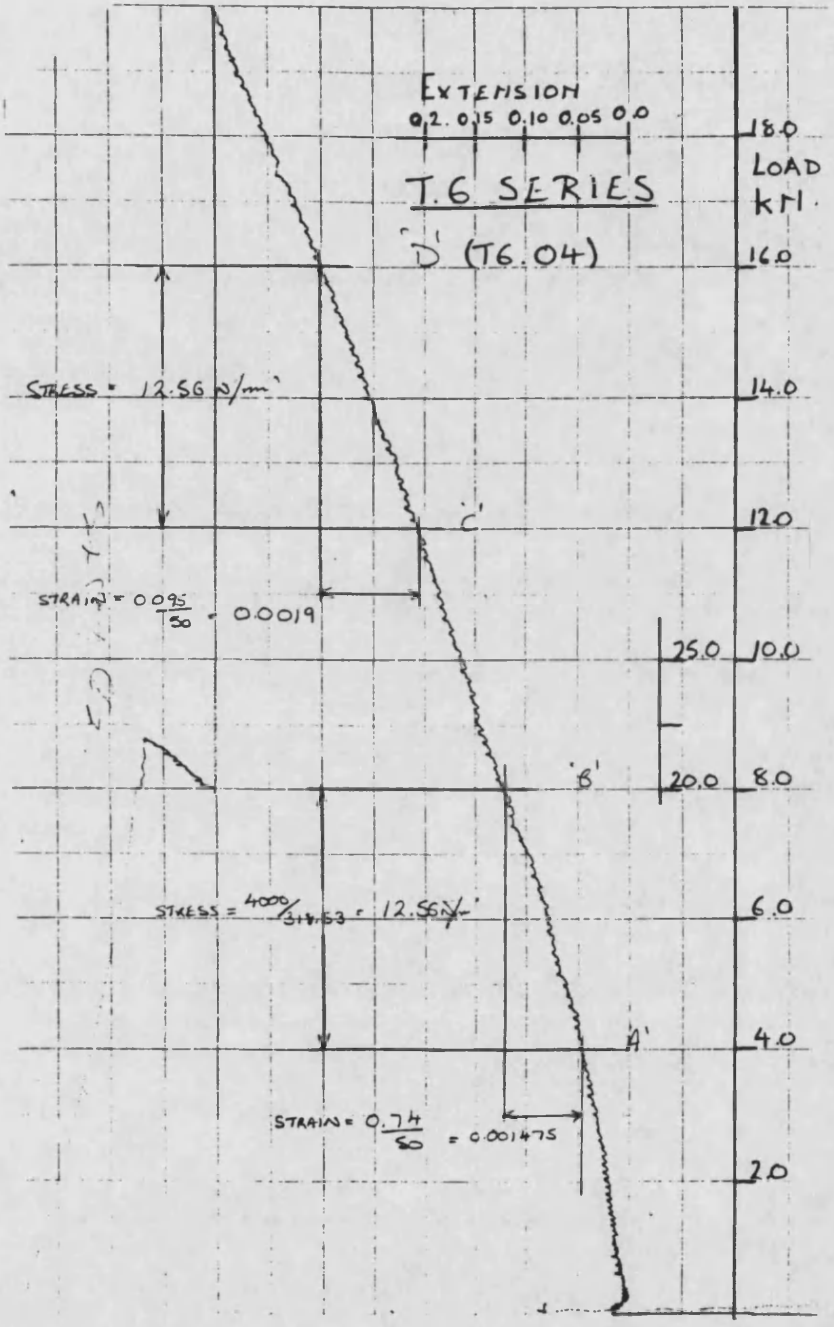


Fig. A10.11 Tensile Tests : CFRC T.6 Series. 200mm long x 6mm thick samples, PVA added to the cement paste. (V_f = 0.047).

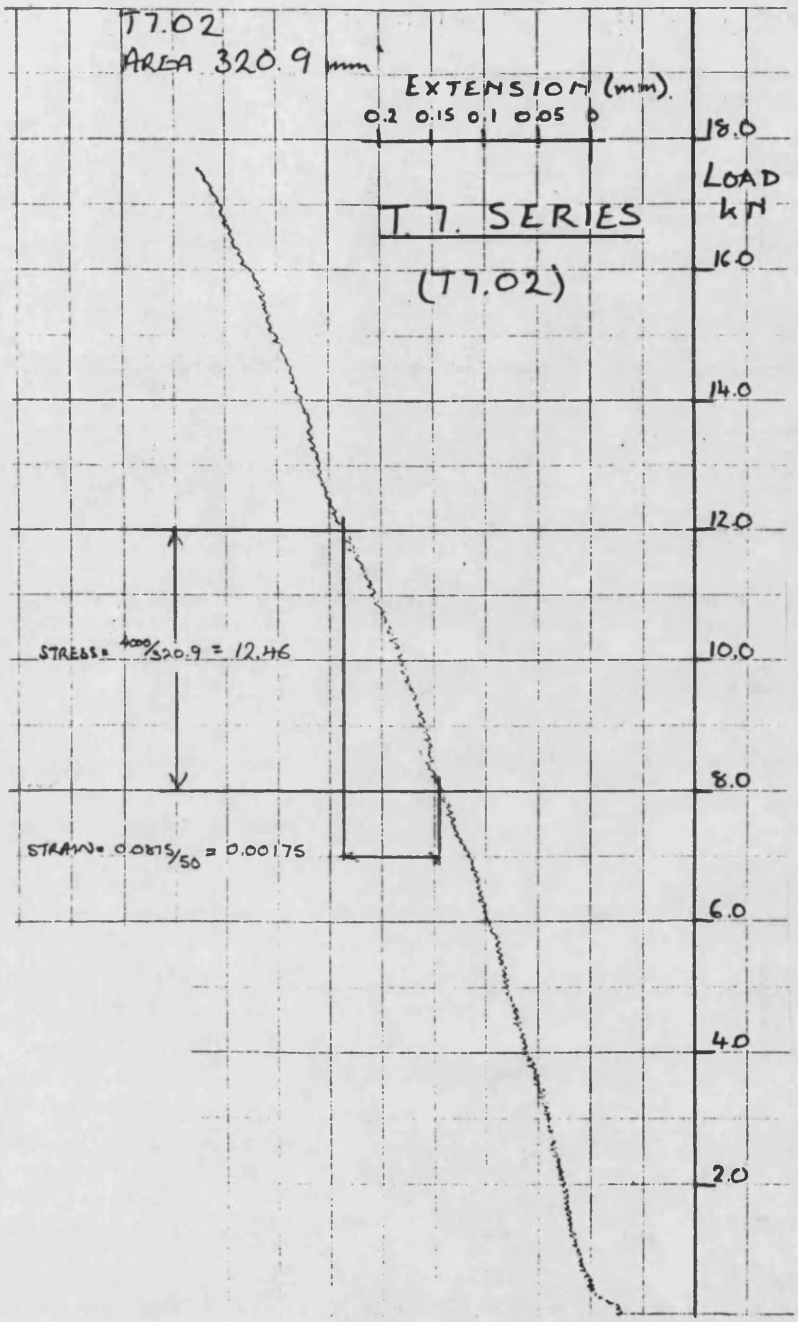


Fig. A10.12 Tensile Tests : CFRC T.7 Series. 200mm long x 6mm thick samples, Alternative (Non water soluble) PVA added to the cement paste. (V_f = 0.047).

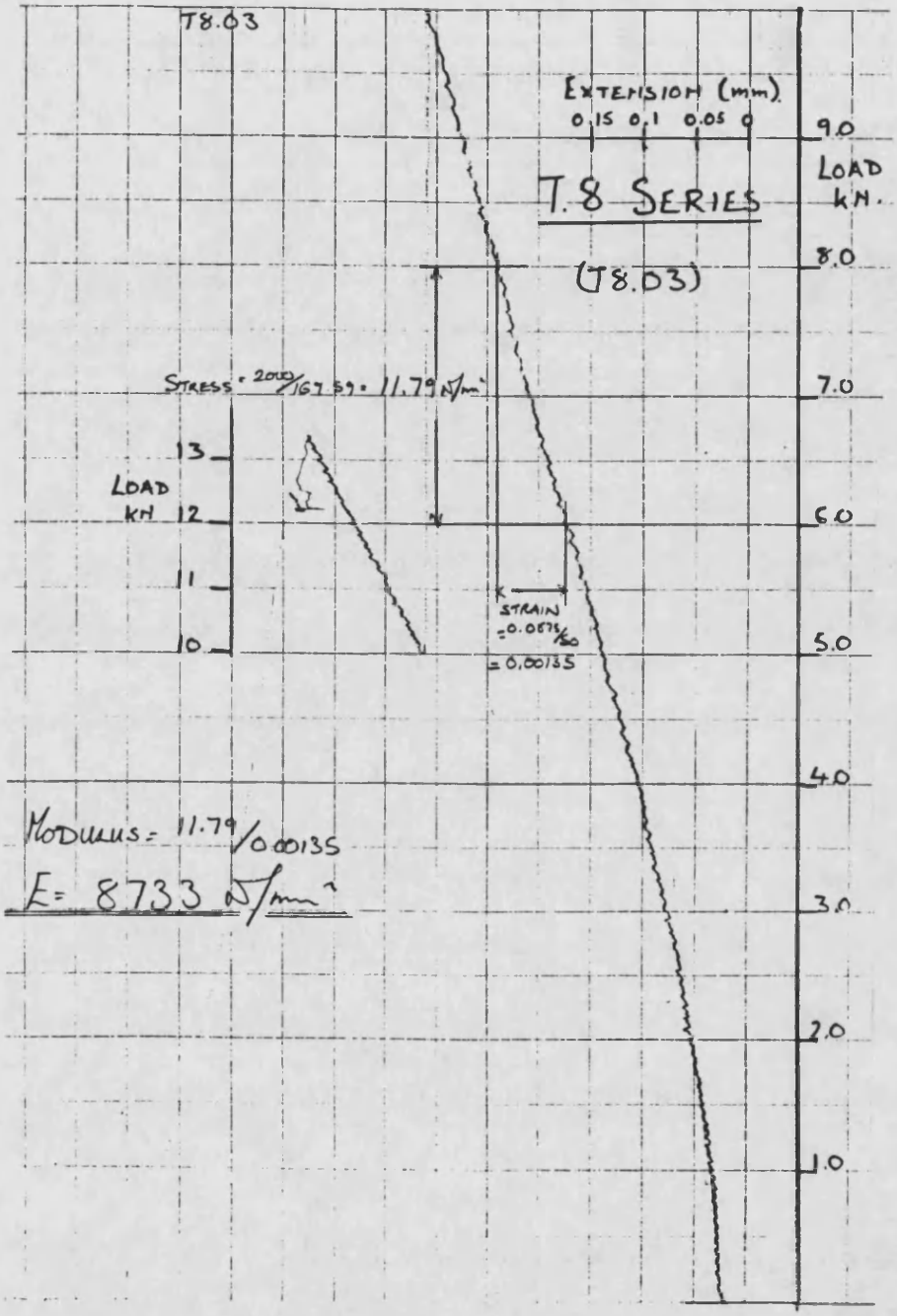


Fig. A10.13 Tensile Tests : CFRC T.8 Series. Improved fibre distribution. (V_f = 0.043).

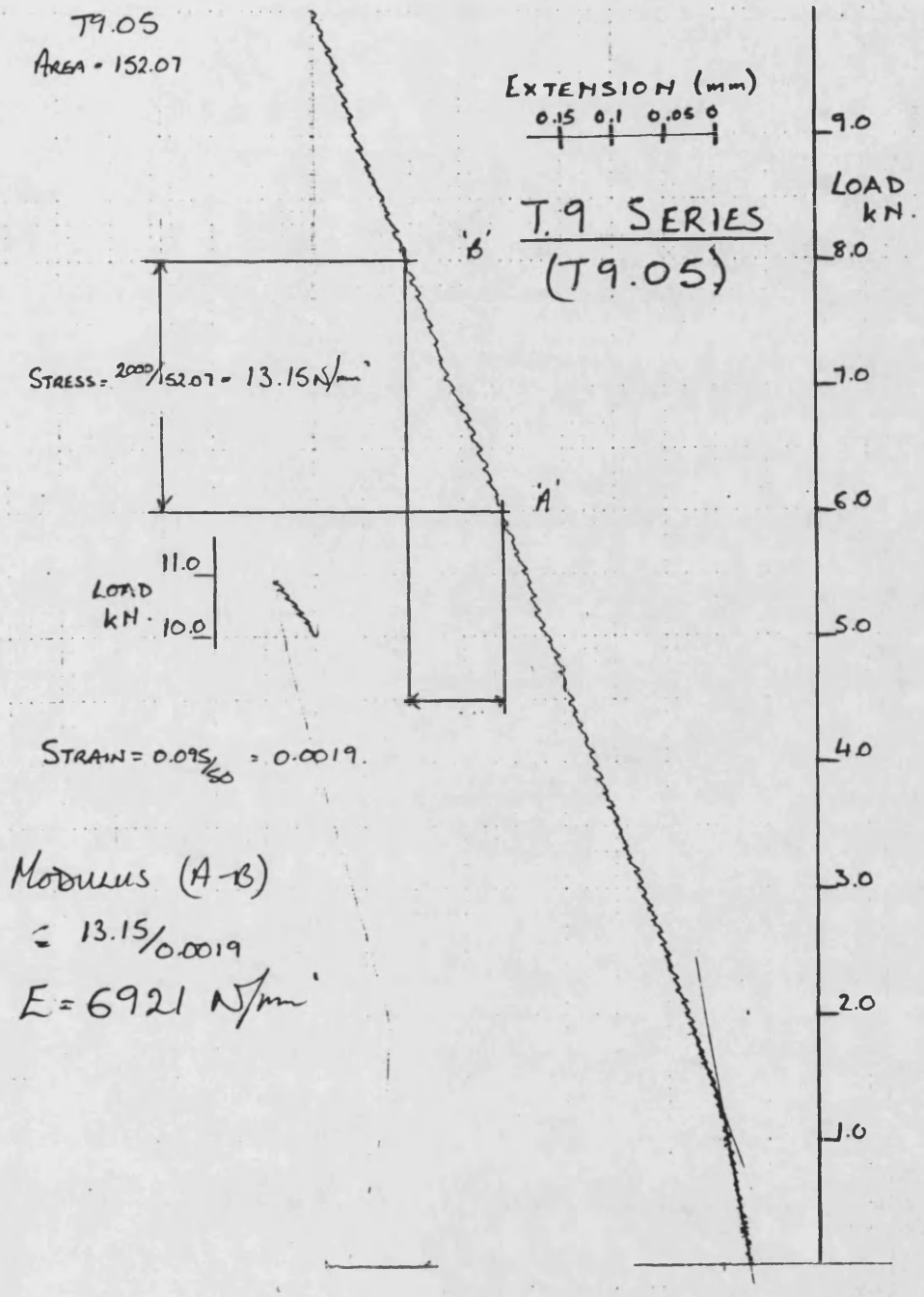


Fig. A10.14 Tensile Tests : CFRC T.9 Series. Tested at age 41 days. (V_f = 0.040).

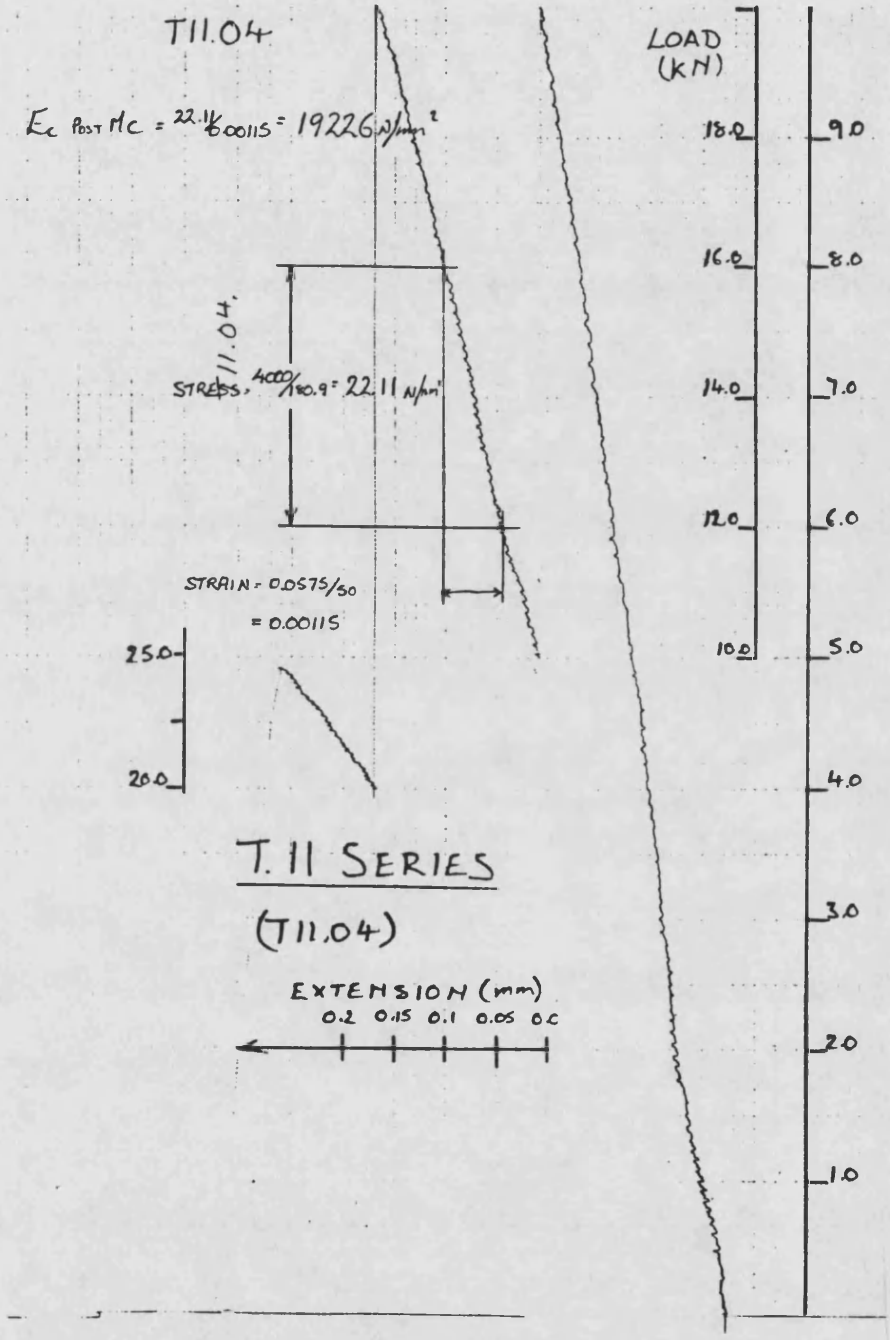


Fig. A10.15 Tensile Tests : CFRC T.11 Series. Fibre volume fraction increased to V_f = 0.09.

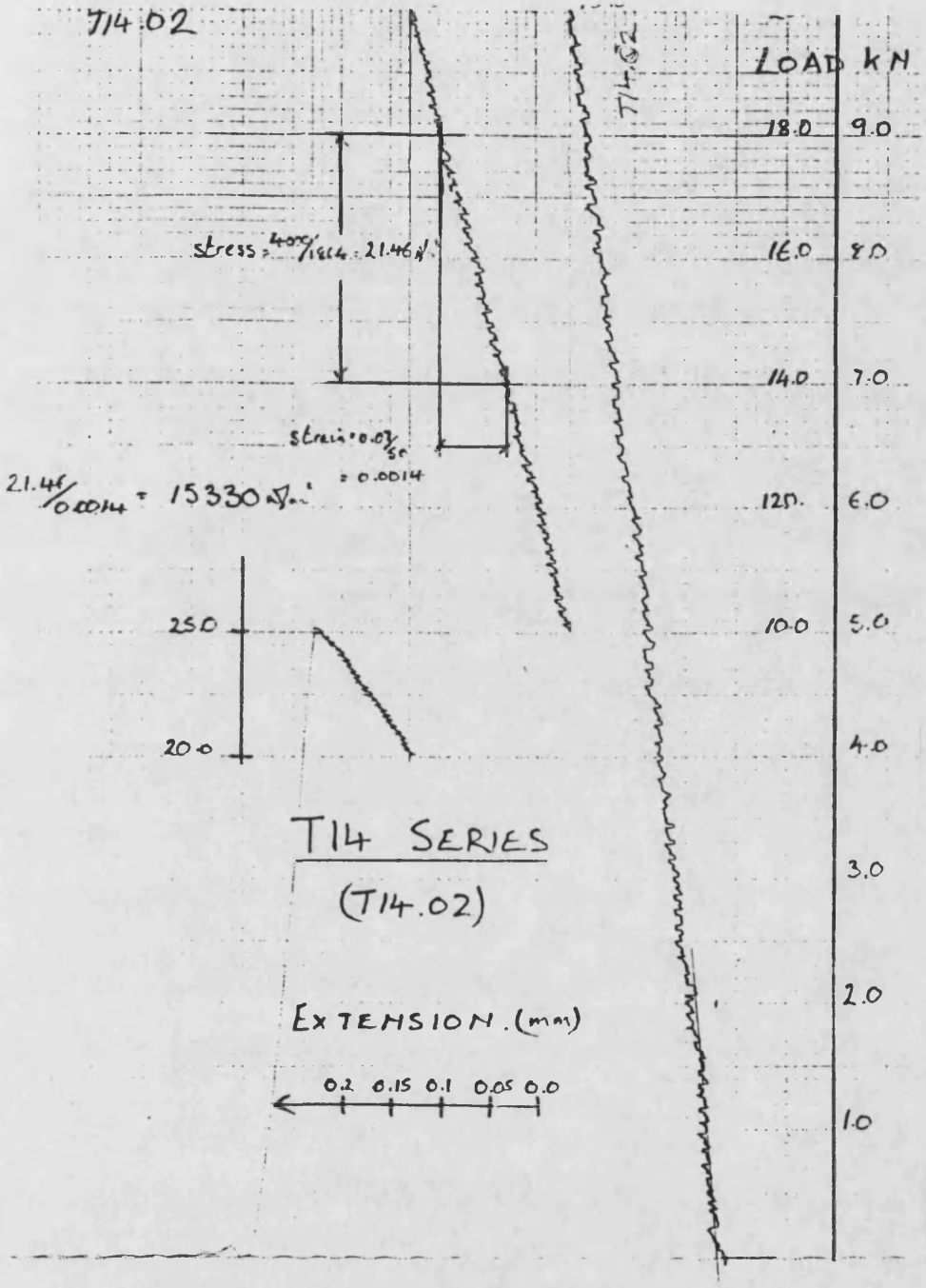


Fig. A10.17 Tensile Tests : CFRC T.14 Series. Increased resin/water ratio. (V_f = 0.08).

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